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MOTION-PICTURE PROJECTION WITH A PULSED LIGHT SOURCE

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Present-day motion-picture projectors are still almost invariably equipped with a continuously burning light-source — usually a carbon arc — the light from which is interrupted twice per frame period by a rotary shutter in order to obtain a stationary picture free from flicker. This article describes an illumination system in which the light source is a super-high-pressure mercury-vapour lamp operated by current pulses, and which dispenses with the need for a shutter.

As long ago as 1938 Philips introduced a motion-picture projector in which the light source was a discharge lamp, viz. a water-cooled super-high-pressure mercury-vapour lamp [1]). This lamp, which was fed by direct current and consumed 1000 watts (2 A, 500 V), replaced the conventional carbon arc. Both types of light source combine small dimensions of the radiant element with great brightness, a characteristic which is essential for application in film projectors [2]). All cinema-goers know that satisfactory projection can be achieved with the carbon arc. Nevertheless, this light source has certain serious drawbacks. In the first place, it requires constant attention from the projectionist [3]). The arc must be allowed to burn for several minutes before use, and the carbon electrodes must be long enough to last for the duration of the film. The incandescent ball of gas in the crater of the positive electrode, which is the main source of light emission, shows a tendency to shift its position with respect to the mirror focus. If the projectionist does not intervene, the result is a noticeable diminution of luminous flux on the screen and a change in the colour of the light. Furthermore, an exhaust system is required for removing the combustion products, but even this cannot prevent deposits forming at undesired places. The carbon arc also causes considerable heating of the film, at least of the picture areas; the edges remain cold. As a result the film buckles slightly, an effect which is accentuated by the fact that it is chiefly the photographic emulsion that absorbs the heat, and not so much the transparent base. This buckling adversely affects the sharpness of the picture — a drawback which is more noticeable nowadays than formerly. There are two reasons for this. Firstly, present-day films are generally made of non-inflammable material, and this buckles more than the material previously used. Secondly, there is a tendency to use faster projection lenses, which have less depth of focus. The fact that the film buckles is therefore more serious and it is more difficult to obtain a picture of uniform definition on the screen.

Compared with the carbon arc the super-pressure mercury lamp has appreciable advantages. It requires much less attention from the projectionist; in fact, without much trouble its operation can be made largely automatic. With the present shortage of skilled personnel, this is an attractive feature. A discharge lamp of this kind produces no unwanted deposits, thus dispensing with the need for an exhaust system, and it heats the film much less then a carbon arc with the same luminous flux, for one reason because the lamp produces much less infrared radiation. The lamp house, too, is much smaller than that for a carbon arc. Water-cooling is required, but this complication is more than offset by the advantages mentioned. In any case, the

[1]) Described by G. Heller in Philips tech. Rev. 4, 2-9, 1939.
[2]) See e.g. T. J. J. A. Manders, Incandescent lamps for film projection, Philips tech Rev. 8, 72-81, 1946, and also the article cited in footnote [1]).
[3]) See, for example, Mitchell's manual of practical projection, International Projectionist Publishing Co., New York 1956, pp. 112-117 and pp. 177-206.

use of high amperage carbon arcs also calls for water-cooling of the film gate. Still higher currents require that the positive carbon contact, too, be cooled.

The fact that the mercury lamp was unsuccessful in its first attempt to rival the carbon arc was mainly due to the deficiencies at that time in its luminous flux, in its rendering of red colours and in its reliability. The life of a mercury lamp ends fairly suddenly, and just when it will end cannot be predicted with any certainty. Consequently the lamp could not be changed in good time and its possible failure during a performance was something that had to be accepted. With the projector of 1938 it took some tens of seconds before the stand-by lamp came into operation. In the following we shall describe a new film illumination system using a super-pressure mercury lamp which overcomes these drawbacks whilst preserving the favourable features. The new system in fact possesses certain important additional advantages, including a very flicker-free picture and an improved efficiency. Some particulars of the lamp itself will also be mentioned. The illumination system can be incorporated into a projector of a new design, discussed elsewhere in this issue [4]). A photograph of this projector, type FP 20 S, equipped with the new illumination system, is shown in *fig. 1*.

The illumination system

As mentioned, the illumination system contains a water-cooled super-pressure mercury lamp as light source. This discharge lamp consists of a small tube of fused silica (length 8 cm, max. diameter 5.6 mm) in which a linear discharge is maintained between the electrodes (spacing 17 mm). The light output of the lamp increases more than proportionally with the power consumed, since the efficiency of high-pressure mercury lamps increases with the power supplied per unit length of discharge [5]). Higher loading improves the colour rendering at the same time, the reason being that the share of the continuum in the emitted light increases with respect to that of the line spectrum. Unfortunately the life of the lamp is thereby shortened, mainly because of the higher temperature of the fused-silica wall. In the projector brought out in 1938 this set a limit to the quantity and the quality of the light output. At the time that this projector was developed an attempt was already made to solve the heat problem by loading the lamp intermittently instead of continously. In motion-picture projection this is an attractive proposition in as much as the illumination of the film must in any case be interrupted twice during each frame period: once in order to pull down the film from one frame to the next without this being visible on the screen, and a second time in order to increase the number of light pulses per second sufficiently to prevent the picture from flickering [6]). The energy consumed by the lamp during the interruptions yields no useful light. If the lamp is loaded only when the generated light is usefully employed, the instantaneous load can be raised whilst maintaining the same

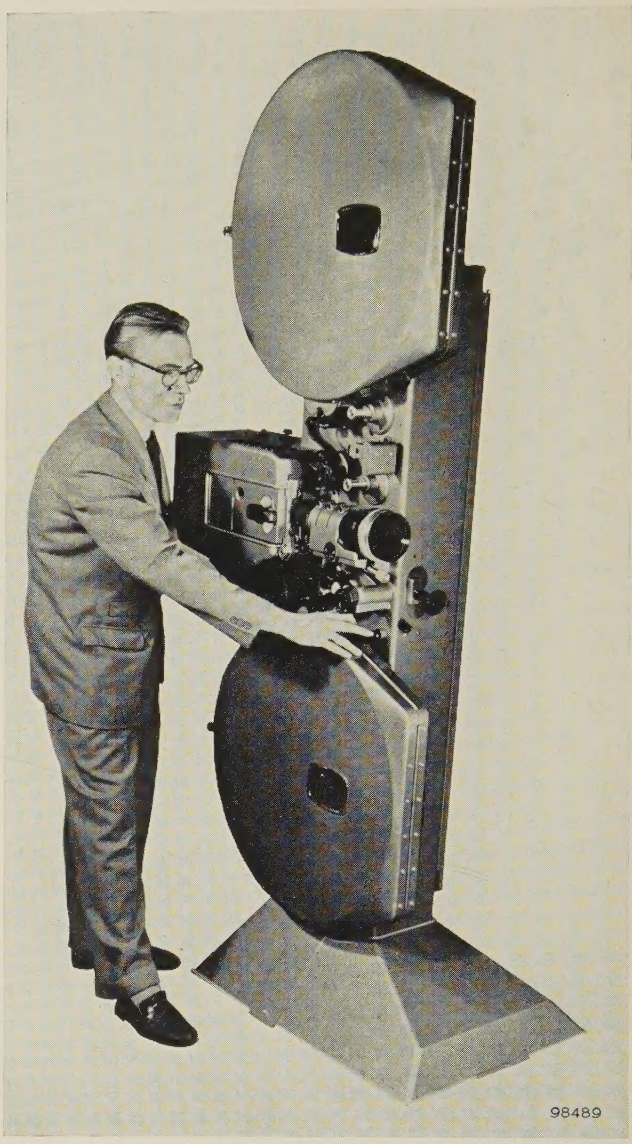


Fig. 1. The new Philips motion-picture projector, type FP 20 S, provided with the new illumination system which is the subject of this article. The projector itself is discussed elsewhere in this issue [4]).

[4]) See the following article in this issue: J. J. Kotte, A motion-picture projector of simplified design, Philips tech. Rev. **21**, 83-77, 1959/60.

[5]) See e.g. W. Elenbaas, Fifty years of the high-pressure mercury vapour lamp, Philips tech. Rev. **18**, 167-172, 1956/57.

[6]) For a detailed discussion of this phenomenon, see: J. Haantjes and F. W. de Vrijer, Flicker in television pictures, Philips tech. Rev. **13**, 55-60, 1951/52.

mean load. The result is more useful light, and moreover the changed spectral distribution of the light provides better colour rendering. The luminous intensity of a mercury lamp follows current variations virtually without inertia. When fed with current pulses, then, the lamp flashes on and off synchronously. This makes it possible to dispense with the rotating shutter which, in the conventional continuously-burning carbon arc (or other source), intercepts the light twice per frame.

Tests with a pulsed mercury lamp were initially disappointing. The life of the lamp was found to decrease sharply when the instantaneous load was raised, even though the mean load remained unchanged. Only after a great deal of development work on the lamp, and careful matching of the pulse generator to the lamp, was it possible to achieve an acceptable life with an instantaneous load high enough to ensure good colour rendering. The final version of the lamp represents a compromise between useful life on the one hand and light output (determined by the *mean* load) and colour rendering (determined by the peak amplitude of the current pulses) on the other. The choice fell on a mean load of 800 W with current pulses of about 15 A peak amplitude. The mean life is then 33 hours. The luminous flux incident on the screen is equal to that from a 60 A carbon arc, and is therefore adequate for the majority of cinemas; the colour rendering, too, is entirely satisfactory. The lamp has been given the type designation SPP 800 W.

Increased projection frequency

We have already mentioned as a particular advantage the very flicker-free picture obtained. This is due to the light source flashing *three* times per frame (*fig. 2*). The frequency is thus 72 flashes per second instead of the usual 48 (the number of frames per second remains unchanged of course). The sensitivity of the eye to flicker increases with the brightness of the picture, and moreover the periphery of the retina is more sensitive to it than the central part. The lack of flicker in the picture from the new projector is therefore particularly noticeable in the brighter projection of wide-screen pictures, such as "CinemaScope."

The higher frequency of 72 flashes per second is in principle also possible with a continuously burning light-source if a three-bladed shutter is used. The resultant loss of light, however, would be unacceptable. With a film-transport mechanism employing the usual four-slot Maltese cross, the shutter would then intercept 75% instead of 50% of the light output (see *fig. 3*).

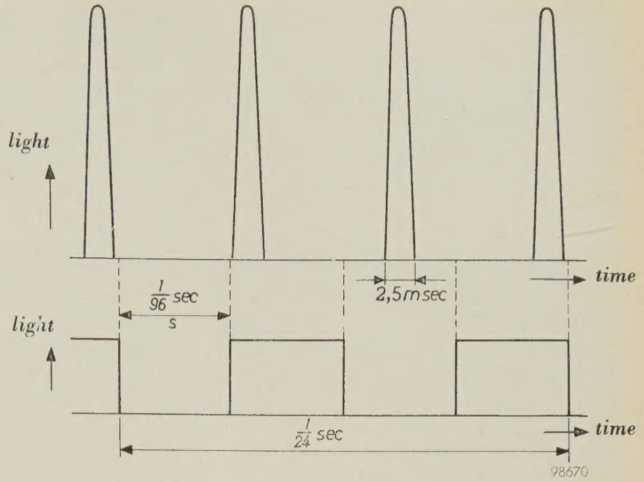


Fig. 2. Distribution over one frame period (1/24 sec) of the three light pulses from the mercury lamp type SPP 800 W (above), and (below) distribution of light periods over a frame period in a normal projection system with shutter. The film is transported during the interval denoted by *s*.

Lamp holder and turret

Fig. 4 shows a dismantled lamp holder together with a type SPP 800 W lamp. The components are so made that they mate together correctly without any adjustments during assembly. The round glass window in front of the lamp is a filter which absorbs ultraviolet radiation. The cooling water that flows over the lamp also passes over the filter, thus dissipating the heat generated in it. Of the little infra-red radiation emitted by the lamp the major part is absorbed by the coolant. The heating of film and film gate is therefore slight.

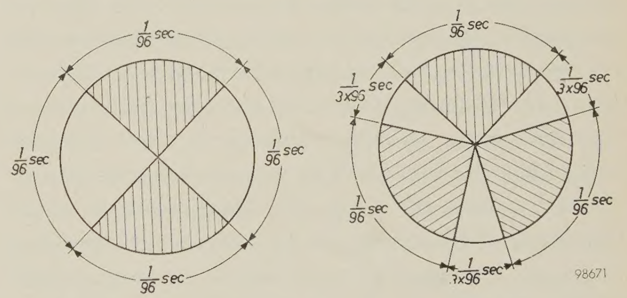
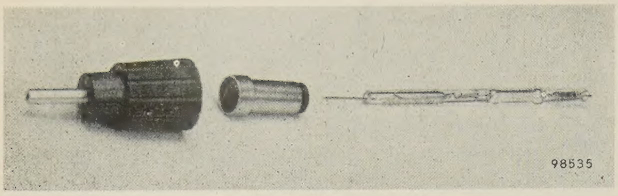


Fig. 3. The theoretical loss of light caused by a shutter that completes one revolution per frame period is equal to the fraction of 360° covered by the blades jointly. Since the fundamental frequency of the illumination cycle is mainly responsible for the nuisance of flicker, the shutter blades must be identical; otherwise the fundamental frequency of the illumination cycle would be equal to the frame frequency (24 per second). The film-transport mechanism is almost invariably a normal four-slot Maltese cross [7]). The frame-shift period must then be ¼ of the total period per frame, so that each shutter blade must cover 90°. With a two-bladed shutter (left) the theoretical light-loss is thus 50%, and with a three-bladed shutter (right) 75%.

[7]) The Maltese cross is described in J. J. Kotte, A professional cine projector for 16 mm film, Philips tech. Rev. **16**, 158-171, 1954/55, in particular fig. 7.



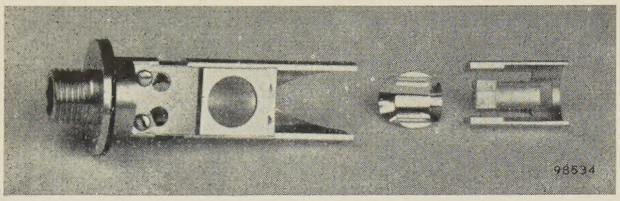


Fig. 4. Dismantled lamp holder. From left to right, above: the head of insulating material with silver contact peg, the centring bush (also acting as coolant seal) and the lamp. Below: the holder with filter for absorbing ultra-violet radiation, the cylindrical reflector, and its holder. The assembled lamp holder is shown in fig. 5.

Fig. 5 shows how two lamp holders are fitted in a "lamp turret". The lower holder, shown removed from the turret, contains the lamp normally in use, the upper holder contains the stand-by lamp. If the lamp in the lower holder becomes defective, the upper one automatically takes its place, the lamp turret pivoting about a horizontal spindle under its own weight. This is effected by the lower lamp being kept in its operating position by a pawl which is tripped when the lamp current cuts out. The cooling water flows in along the spindle around which the lamp turret rotates, and reaches the operative lamp holder via corresponding holes in the spindle and the turret. The cooling water is thus automatically switched to the stand-by lamp as soon as this is called into operation. The same applies to the electric supply. The stand-by lamp takes over so quickly as to be imperceptible to the audience watching the screen. The projectionist notices it, however, from the colour of a transparent sector on the front of the turret. If the projector is operating normally the green sector is visible; when the stand-by lamp enters into operation the red sector appears as a warning to the projectionist. He can now unscrew the lower lamp holder from the turret and replace the lamp whilst the projector remains in operation. Later, when there is a suitable opportunity, he can turn the lamp turret by hand back to its normal position. In this way the useful life of each lamp is exploited to the full, and the performance is insured against the unlikely event of a double lamp failure.

The above implies that, as far as the lamp is concerned, there is no limit to the lengths of film that can be used. This advantage promises to gain in importance in the future. In connection with the risk of fire, film spools and drums were formerly designed to accommodate films not longer than 600 metres. Now that inflammable films are no longer commonly used and have in fact been prohibited in many countries, it is likely that longer lengths of film (up to 1800 metres) will come increasingly into use.

When a lamp holder and its lamp are loaded into the turret, the exposed end of the lamp (see lamp-holder in fig. 5) slides into a hole surrounded by an annular nozzle inside the turret. The electrode pin at this end then presses against a spring-loaded contact, which also acts as a valve shutting off the water supply to the nozzle when no lamp is mounted. The other lamp electrode pin is clamped inside the contact peg at the head of the lamp holder (fig. 4, upper photo). When the lamp holder is in the operating position, this peg lies on a contact consisting of a metal flat partly encapsulated in a block of insulating material. This block is fixed to the lamp house in which the lamp turret is incorporated (*fig. 6*).

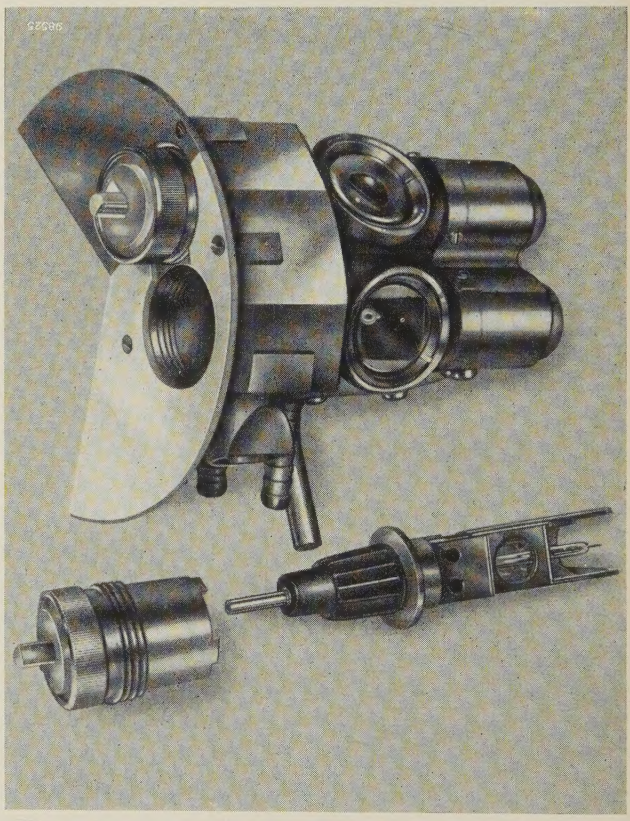


Fig. 5. Lamp turret with two lamp holders. The lower one, which is removed from the turret, contains the lamp normally in use; the upper lamp holder contains the stand-by lamp. The windows in front of the lamps also act as the first condenser lenses. The turret is provided with a red and a green sector, which indicate to the projectionist at a glance which lamp is in operation.

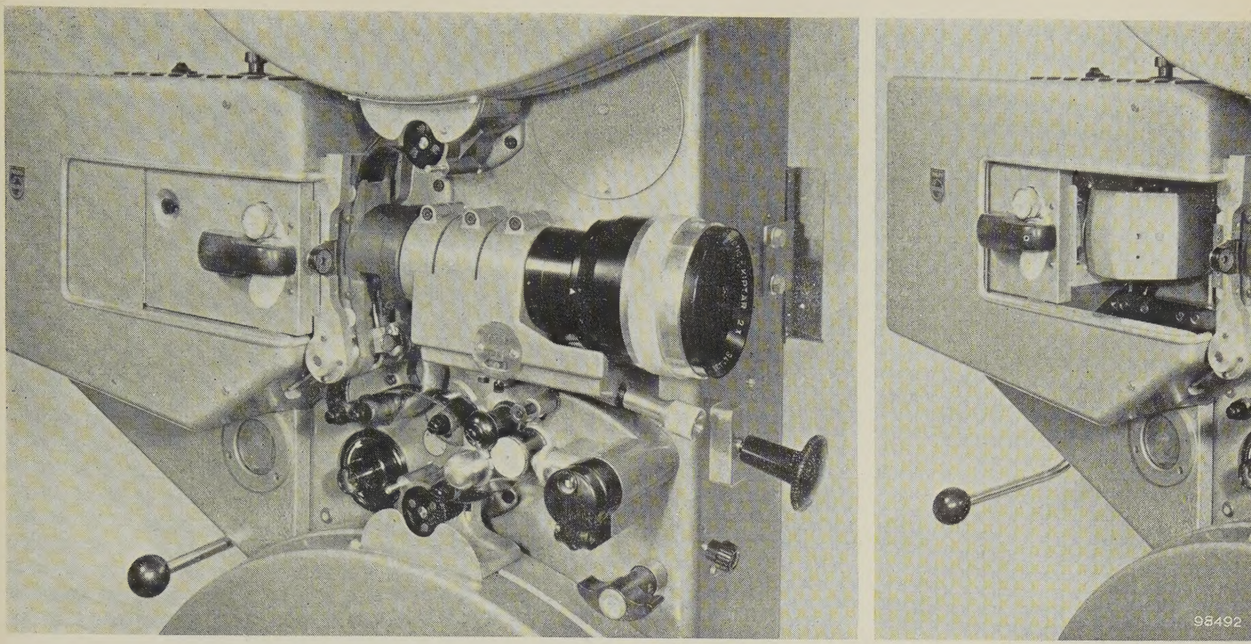


Fig. 6. Part of cine-projector fitted with the pulsed light-source illumination system. Above the block of black insulating material, which carries the positive contact, can be seen the cap which encloses the lamp holder with the stand-by lamp, in the turret. The photograph shows on the left the lamp house in the position for film projection. By means of the lever (bottom left) the lamp house can be moved backwards. The same lamp then serves for projecting lantern slides (right).

The optical system

The optical system is shown schematically in *fig. 7*. Seen from the light source, the film and aperture are located directly behind the condenser lenses. The effective diameter of the condenser is therefore only slightly larger than the diagonal of a film frame (26 mm in standard films). Since this implies a small condenser, the light source must be close to it in order to ensure that the condenser receives a sufficient part of the luminous flux. In this way a very compact assembly is obtained. The fact that it is technically feasible is due in the first place to the small dimensions of the lamp and in the second place to the simple way in which the ultraviolet and infra-red radiation is intercepted and rendered harmless. This radiation would otherwise be largely absorbed by the condenser and would damage it. Precisely because it is so small, the condenser is in any case severely heated merely by the high flux of visible light, of which it absorbs a very small fraction [8]).

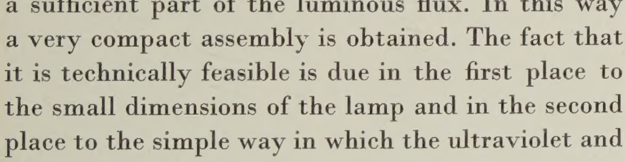


Fig. 7. The optical system. *A* cylindrical mirror, *B* linear light-source, *C* diaphragm, *D* ultraviolet-absorbent filter, *E* first condenser lens, *F* second condenser lens, *G* film aperture, *H* film, *J* projection lens, *K* image of light source projected by condenser.

The condenser system consists of two lenses, the first of which also acts as a water-tight window for the lamp turret. Behind the light source there is a cylindrical reflector of aluminium sheet (0.3 mm thick). Since this mirror provides more than 60% of the projected light, it is essential that its reflective power should not be diminished. For this reason a new reflector is supplied with every new lamp.

In a projection system as in fig. 7 the condenser is always arranged to form an image of the light source at the position of the projection lens. It is not the image formation itself that is important (the image is usually unsharp) but the fact that a pencil of light emanating from an arbitrary point of the light source has a small cross-section *at* the projection lens. This being so, if the central ray of

[8]) With conventional light-sources a different and less compact system is employed for film projection. The two systems are compared in the article mentioned in footnote [1]) and more recently in: P. M. van Alphen and M. Bierman, A mirror condenser lamp for 8 mm projectors, Philips tech. Rev. **19**, 233-235, 1957/58.

a pencil from any point of the source passes through the projection lens, all or almost all of that pencil of light does so. The optical centre of the condenser falls virtually in the film and hence virtually in the focal point of the projection lens (the screen is a considerable distance away). Consequently, the relative aperture of the projection lens determines what length of the light source is effective in contributing to the projected light. In the pulse-operated projector the central rays emanating from the ends of the discharge make such large angles with the axis that the projection lens should have at least a relative aperture of *f* 1.4 in order to transmit them. A normal value for the relative aperture of a projection lens is *f* 2. If such a projection lens is used, the extremities of the light source do not contribute to the luminous flux on the screen. This is done deliberately, for it precludes that the luminous flux incident on the screen gradually diminishes with the age of the lamp, as a result of the darkening of the fused-silica wall (a re-crystallization or devitrification phenomenon) which begins at the extremities of the discharge.

To avoid needless heating of condenser and film gate, a diaphragm is interposed between the lamp and the condenser. This is matched to the projection lens and intercepts the unused light. This diaphragm also serves as holder for the ultraviolet filter; it can be seen in fig. 4.

Projection of lantern slides

The same illumination system is employed for the projection of lantern slides. The slide holder is located at the other side of the projector. In order to convey the light to that side, the lamp house is mounted on rails. By means of a lever (see fig. 6) the lamp house can be shifted backwards. A plane mirror is thereby moved into the path of the rays at an angle of 45° (right, fig. 6). (When the lamp house is returned into position for film projection, this mirror folds upwards again.) The light reaches the lantern slide via the lens *E* (*fig. 8*), a second 45° mirror *F* and the lens *G*, whence it is transmitted to the lantern slide projection lens. In *fig. 9* the lamp house is shown in an intermediate position, in which the mirror has not yet descended.

The lamp is also pulsed for the projection of lantern slides, in order to benefit from the improved colour rendering resulting from pulsed operation.

Luminous flux and efficiency; light distribution

With a standard film gate, but with no film in it, and using a projection lens of the Petzval type

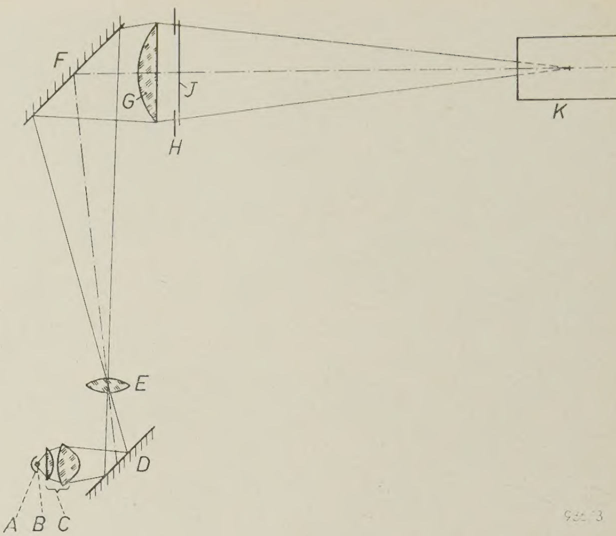


Fig. 8. Path of rays in the projection of lantern slides. *A* cylindrical mirror, *B* light source, *C* condenser, *D* plane mirror, *E* lens, *F* plane mirror, *G* lens, *H* mask, *J* lantern slide, *K* projection lens for lantern slides.

having a relative aperture of *f* 2, and a pulsed light-source, operated at 800 W, the system delivers a luminous flux on the screen of 4800 lumens. With a projection lens of the same type, but having a relative aperture of *f* 1.6, the luminous flux on the screen is as high as 6000 lumens [9]). The efficiency in these two cases is thus 6 and 7.5 lumens per watt, respectively. The earlier-mentioned 1938 projector, with a lens of relative aperture *f* 2 and

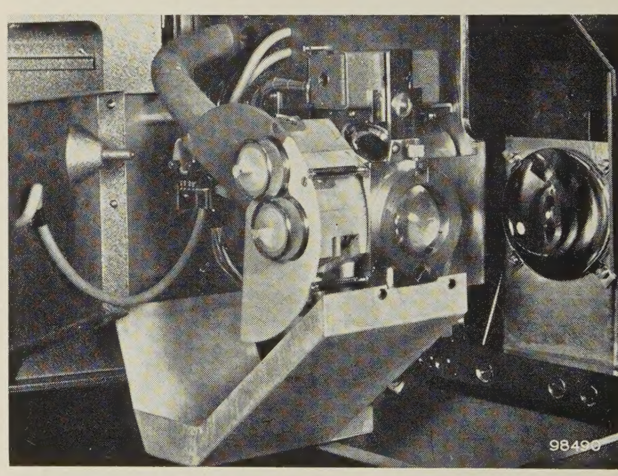


Fig. 9. Lamp-house opened to position between that for film projection and that for lantern slide projection. The 45° mirror has not yet descended into the path of the rays. Below can be seen the tray for collecting any leakage water. The cooling water is fed in through the thick hose visible above.

[9]) A projection lens system of the Petzval type consists of four lenses. Systems having a relative aperture of *f* 1.6 are usually more complicated and contain six or seven lenses; the gain due to the greater relative aperture is then partly lost as a result of higher losses in the lens system.

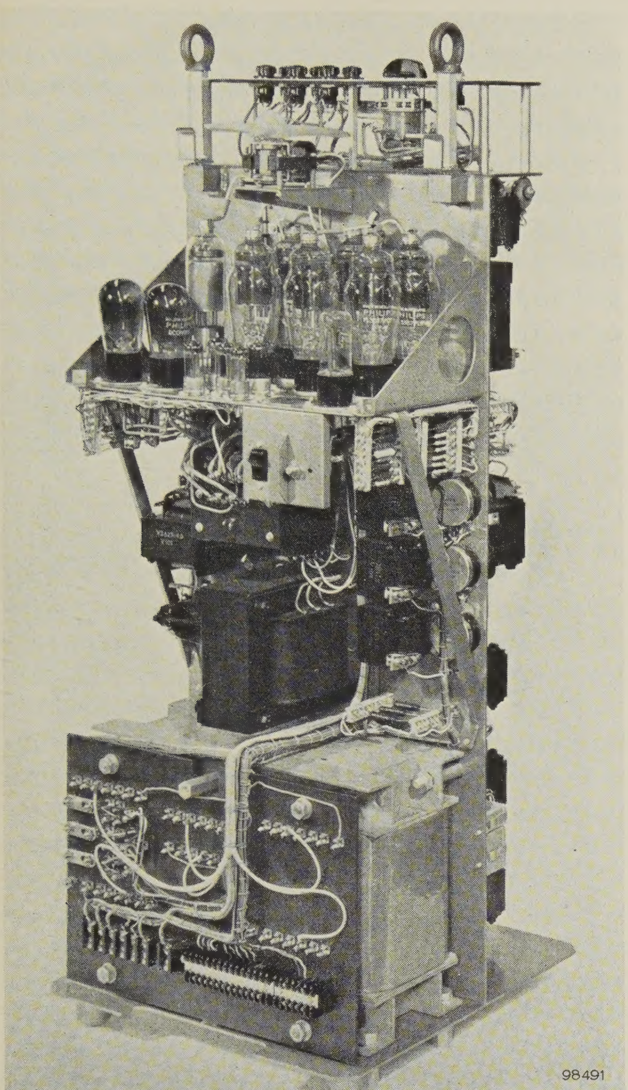


Fig. 10. Power pack (pulsator) for the pulsed-source illumination system, with protective hood removed.

a rotary shutter, gave a total flux of 2900 lumens [10]). The lamp consumed 1000 W, so that the efficiency was 2.9 lm/W. The more than double efficiency of the pulsed illumination system is, of course, mainly attributable to the fact that light is only produced when it is usefully employed. For carbon arcs of 45 and 60 amperes the flux on the screen is respectively 3500 and 5500 lumens. The efficiency of a carbon arc is approximately 2.5 lm/W.

According to the practice in projection technique, the fluxes mentioned are based on measurements of the luminous intensity in the middle of the screen. Since the luminous intensity always decreases from the middle towards the edges, the actual flux values are lower. In the case of the pulsed lamp the decrease towards the edges amounts at the most to 10% in the horizontal direction and to between 15 and 20% in the vertical direction. (The smaller horizontal decrease is due to the elongated form of the horizontally positioned lamp.) This is appreciably less than in the case of the carbon arc, where the decrease for the same flux values is 25% horizontally and about 20% vertically [11]). For the same values of luminous flux, as given according to the normal practice, the true luminous flux of the pulsed system here described is therefore actually greater than that of a carbon arc.

Power pack (pulsator)

The power pack which supplies the current pulses for the lamp (the "pulsator") is shown in *fig. 10.* In the simplified block diagram, given in *fig. 11*, *A* is a six-phase rectifier which charges the capacitor *C* to a voltage higher than the operating voltage of the lamp. At the moments when the lamp is required to flash, a voltage pulse is applied to the grid of thyratron *T*, making the latter conduct. The capacitor *C* thereupon discharges through the lamp.

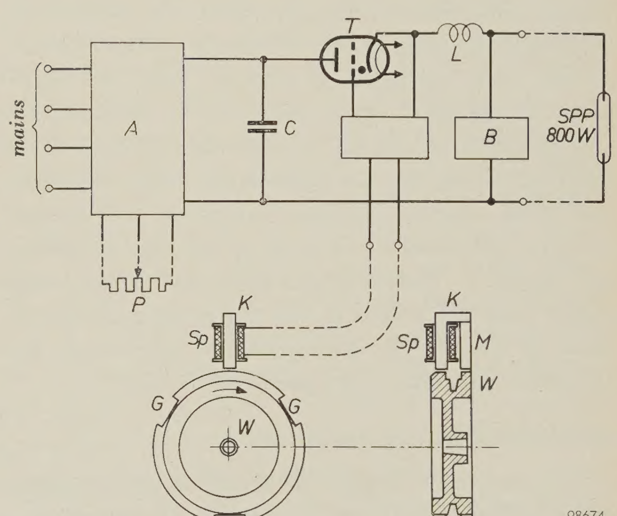


Fig. 11. Simplified block diagram of power-supply system for the pulsed super-pressure mercury lamp, type SPP 800 W. *A* six-phase thyratron rectifier. *P* potentiometer for varying the voltage on the thyratron grids. *C* capacitor which supplies the current pulses. *T* thyratron to whose grid the synchronizing pulses are supplied which are generated in the coil *Sp*. This coil is wound on the soft-iron core *K* and is located in the projector. *W* flywheel of Maltese cross. The grooves *G* in *W* produce in *Sp* three voltage pulses per revolution of the flywheel. *L* inductance which gives the condenser discharge the nature of a damped oscillation, and which together with *C* governs the flash duration. *B* holding-current rectifier; this keeps a small current flowing through the lamp during the intervals when the lamp emits no light.

[10]) In the article cited in footnote [1]) a figure of 2500 lumens is given. This referred to a lens system that was not provided with the low-reflection coated lenses now commonly employed.

[11]) With a carbon arc the decrease towards the edges can certainly be reduced, but only at the expense of the illumination level in the middle of the screen. Some decrease is desirable, as otherwise contrast effects would make the edges of the screen appear brighter than the middle.

The inductance L then tends to produce an oscillation in the circuit. At the moment, however, that the current tries to change direction, the thyratron becomes non-conducting and the lamp is extinguished. The rectifier charges up the capacitor, and upon the arrival of the next voltage pulse on the grid of T the lamp flashes again. At the same time the lamp is fed by the "holding current" rectifier B. This ensures that in the period between the flashes a small current continues to flow through the lamp, thereby keeping the gas sufficiently ionized to ensure that it flashes readily upon the arrival of the succeeding pulse. (If the lamp is cold, the gas pressure is low and so therefore is the ignition potential; switching on the lamp when no holding current is yet flowing therefore presents no difficulty.) The holding current is very low and produces no light of any significance.

The duration of the flash depends on the period of the oscillation produced in the circuit, and this period can be regulated by varying L or C, or both.

Rectifier A operates with six thyratrons. The voltage delivered by the rectifier, and to which C is charged up, can be adjusted by means of a variable bias on the grids of these thyratrons. In this way it is possible to control the amplitude of the current pulses. The variation is effected with potentiometer P (fig. 11), which can either be mounted on the projector or placed at any other desired position, e.g. in the cinema auditorium. Flash duration and peak current together determine the energy per flash and also — at a given number of flashes per second — the average lamp-load. If this load varies from 600 to 800 W, the power pack consumes from 1.3 to 1.6 kW. A comparable carbon-arc installation consumes approximately 3 kW.

Synchronization and protection

The three light flashes per frame must, of course occur outside the pull-down period. The synchronizing pulses for the grid of the thyratron T are therefore derived from the flywheel of the Maltese cross in the projector. This steel flywheel, in which three grooves G are milled (fig. 11) forms part of a magnetic circuit containing, in addition, a permanent magnet M and a soft-iron core K around which a coil Sp is wound. Every time one of the grooves passes this assembly, the magnetic flux is sharply attenuated. The resultant voltage pulse in the coil Sp is applied to the grid of T. The exact moments at which the flashes occur can readily be adjusted by shifting the position of the magnet-core-coil assembly in relation to the flywheel. This can be done whilst the projector is operating.

Precautions are taken to ensure that the lamp, in the event of a fault, cannot burn continuously directly from the rectifier A, and also to prevent it operating only from the holding-current rectifier.

When the apparatus is switched over for lantern-slide projection, the projector is not running. The synchronizing pulses for the thyratron T are then derived directly from the mains. Pulses are then delivered with twice the mains frequency. On 50 c/s mains this means that there are 100 instead of 72 pulses per second as for film projection. To avoid overloading the lamp the capacitor voltage is then at the same time automatically reduced such that the average load remains the same.

Automatic change-over

A motion-picture film often consists of two or more reels, and for this reason most cinemas have two projectors installed. When one reel is at an end, the next reel, which is already loaded on the other projector, is switched on without interrupting the projection. A correct "change-over" calls for vigilance on the part of the projectionist. With a projector equipped with the new illumination system the change-over can easily be made automatic. For this purpose an automatic change-over device has been designed. It consists of a base plate on which several microswitches are mounted, and these are operated by cams on a common motor-driven shaft. When one reel is nearly at an end, a warning sign appears in the top right corner of the projection screen, which is the signal for the projectionist to start the motor for the other projector. To automatize the change-over a contact strip is affixed to the film, adjacent to the motor-starting sign, between the edge and the perforations. This contact strip actuates a relay which starts the idle projector turning and switches on at the same time the motor that drives the automatic change-over device. The cams then start to rotate, whereupon 1) picture and sound are switched over after 8 sec, 2) some seconds later the "run-off" projector is stopped and 3) the cam-drive motor is switched off. The automatic device is now ready for the next change-over cycle. This system relieves the projectionist of quite a number of routine operations.

The lamp

The D.C. lamp type SP 1000 W used in the 1938 projector was not the immediate starting point for the development of the SPP 800 W lamp used in the new illumination system. The SP 1000 W type contains a surplus of mercury, that is to say so much that, even when the lamp is burning, only a very

small fraction of the mercury is vaporized. This lamp has a number of drawbacks which become particularly apparent when used for film projection and which will be touched on presently [12]). A start was therefore made on the development of a so-called *dosed* D.C. lamp, that is to say a type containing so little mercury that practically all of it is vaporized when the lamp is burning (*fig. 12*). This work was subsequently diverted to the development of a dosed lamp for *pulsed* operation.

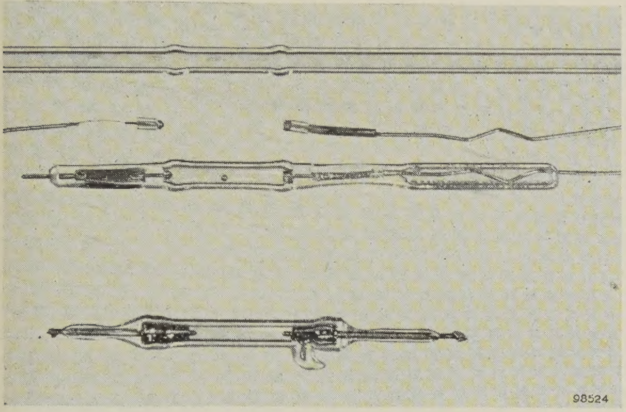


Fig. 12. The dosed super-pressure mercury lamp SPP 800 W for pulsed operation. The photograph shows from top to bottom: the pre-shaped tube of fused silica in which the electrode systems are sealed; the electrode assemblies; and the complete lamp. A fused silica capillary fits over each electrode stem. In the complete lamp the dosed quantity of mercury can be seen in the form of a droplet. Below, the surplus-mercury lamp type SP 1000 W. The mercury can be seen around the electrodes.

There are two chief disadvantages attaching to the lamp containing a surplus of mercury. Before igniting the lamp it is desirable to shake and tap it in order to distribute the mercury uniformly around the two electrodes which project some way into the discharge space. This may prove rather troublesome, particularly in a lamp that has already burnt for several hours. Furthermore, the lamp sometimes burns unsteadily owing to the abrupt rising or falling of the arc voltage. This phenomenon is probably connected with changes in the position of mercury surfaces.

The dosed lamp

A dosed lamp cannot be made by simply taking a lamp identical to the old surplus-mercury type and providing it with a dosed quantity of mercury. The electrodes would then project too far into the discharge space. The distance from the point of an electrode where the discharge is initiated — and where the heat is produced — to the seal would be so great, so that the temperature at this seal would be considerably below the temperature in the discharge. The latter temperature is limited by what the fused silica can stand, and the lowest temperature in the lamp (which determines the mercury vapour pressure) would therefore be lower than in the case when the surplus mercury *is* present. The mercury vapour pressure would therefore not reach the required high value. To produce a dosed lamp in which the mercury-vapour pressure rises just as high as in a surplus-mercury type, the end-wall must be located at approximately the position taken up by the mercury surfaces in the surplus-type lamp (see, fig. 12, below). This represents a problem, however. In the surplus-type lamp the electrodes are tungsten wires. Since these cannot be directly sealed in fused silica, the wires are first sealed in an intermediate glass which, in its turn, is sealed in the fused silica. This form of intermediate seal is not suitable for the dosed lamp because the spaces behind the ends of the electrodes cannot be made small enough, and moreover the intermediate glass seal cannot withstand the necessary high temperature. For this reason a molybdenum-foil seal was adopted, thereby eliminating the need for an intermediate glass. Very thin foils of molybdenum can quite readily be sealed in silica [13]). The foils used here are 10 to 12 microns thick. The lead-in wire is welded to one end of the foil and the tungsten wire electrode to the other end (fig. 12). However a foil seal is itself too weak to secure an electrode with sufficient mechanical strength. On each electrode wire, therefore, is a closely fitting capillary of fused silica. The whole electrode assemblies are then introduced into the fused silica lamp tube and sealed in. The Mo foils then fuse into the silica tube, and likewise the pieces of capillary. This leaves a tiny annular gap around each electrode wire, so narrow that the capilliary still firmly holds the wire.

Care must be taken that the temperature developed in the gaps round the electrodes is not below that of the wall near the discharge. With this in mind the diameters of the electrode wires are chosen so as to ensure that the lamp current generates the right amount of heat in the wires for this purpose. Another problem is the dissipation of heat. In the surplus-type lamp the mercury around the electrodes is responsible for considerable heat dissipation by conduction; in the dosed lamp the heat must be dissipated mainly by radiation. Each of the

[12]) The SP 1000 W lamp is well suited to other applications, for example in shipyards for apparatus in which the lamps are not switched on and off very frequently.

[13]) D. Gabor, D. R. P. 573 448, 1931. See also J. L. Ouweltjes, W. Elenbaas and K. R. Labberté, A new high-pressure mercury lamp with fluorescent bulb, Philips tech. Rev. **13**, 109-118, 1951/52, especially p. 115.

electrodes is therefore fitted at the end with a head to obtain a sufficiently large heat-radiating surface. The edges of the electrode heads are so close to the wall of the lamp that it is necessary to widen the bulb slightly at this position. Otherwise the bulb temperature here would become so high as to cause rapid devitrification of the silica. In fig. 12 it can be seen that the widening of the bulb at these positions is effected before the electrodes are sealed in.

As stated, the dosed lamp was developed with an eye on pulsed operation. DC pulses impose a heavier load on a discharge lamp than ordinary DC operation. The life of a lamp intended for DC operation is therefore almost invariably very much curtailed if the lamp is pulsed at the same mean power. One reason for this is the heat generated in the electrode seals. The heat generated at any given instant is, of course, proportional to the square of the current, and this means that, at the same mean power, the heat generated is greater the shorter the duration of the pulses. One cannot reverse the argument however, and conclude that a lamp which has a good useful life under pulsed operation will have a much longer life if operated on direct current. In order to obtain the most favourable conditions for DC operation various factors make it necessary to adopt, among other things, different dimensions for the electrodes.

One of the most important points in the development of the pulsed lamp was the control of manufacturing conditions. For motion-picture projection there is a constant demand for more light, and lamps for this purpose are always loaded to the utmost. This means that any manufacturing deviation of the lamp from the exact design almost invariably means a lamp of considerably shorter life. Mechanization of the manufacturing process was therefore just as necessary to obtain a uniform product as it was to lower the production costs. The average life of 33 hours mentioned at the beginning of this article applies under average conditions encountered in motion-picture projection, that is to say with the lamp being switched on or off every quarter of an hour (this period was determined by counting the number of occasions the lamp was actually switched on and off in an arbitrary cinema). In spite of all precautions, the spread in lifetimes is considerable. This presents no practical difficulties, however, because of the automatic change-over to the stand-by lamp.

At a mean load of 800 W the lamp gives a light output of about 40 000 lumens. The fact that the SPP 800 W lamp gives good colour rendering can really only be demonstrated by viewing a colour film projected with this light source. The improvement compared with the SP 1000 W is in fact much greater than might be expected from a comparison of the light-flux in spectral bands for the two types of lamp as shown in the *table*. (This spectral-

Table. Relative luminous-flux of spectral bands for the lamps SPP 800 W and SP 1000 W. The visible spectrum is divided into eight bands after Bouma [14]). For comparison, the distributions are also given for daylight and for the high intensity carbon arc. The colours are indicated at the foot of the table.

Section	1	2	3	4	5	6	7	8
Wavelength range mμ	400-420	420-440	440-460	460-510	510-560	560-610	610-660	660-720
SPP 800 W	0.025	0.28	0.50	4.24	43.7	46.6	4.3	0.28
SP 1000 W	0.042	0.53	0.87	4.6	52.6	37.6	3.4	0.25
Daylight	0.025	0.26	0.91	11.1	40.8	36.2	9.9	0.73
Arc	0.050	0.27	0.97	10.2	43.7	33.2	10.6	0.94

436 495 566 589 627

violet blue green yellow orange red

band method was devised by Bouma [14]) who divided the whole visible region of wavelengths into eight sections, in a specified way, taking into account the properties of the eye.) It can be seen from the table that the SPP 800 W lamp, as compared with the SP 1000 W, shows appreciably less luminous output at the blue end of the spectrum, and a greater output at the red end.

[14]) See e.g. P. J. Bouma, Colour reproduction in the use of different sources of "white" light, Philips tech. Rev. **2**, 1-7, 1937.

Summary. The water-cooled super-pressure mercury lamp has many properties that make it more attractive as a light source for motion-picture projection than the conventional carbon-arc. In a normal projector, however, in which the shutter intercepts about 50% of the light, the light yield is rather on the low side for large theatres, whilst in colour projection less than justice is done to the red colours. This article describes an illumination system in which the mercury lamp is pulsed, thus producing light only when it can be usefully employed and rendering a shutter superfluous. At the same power consumption, this gives twice as much light on the screen as obtained from a continuously burning lamp, half of whose output is intercepted by a shutter. With a projection lens having a relative aperture of f 2, the luminous flux on the screen is 4800 lumens, and with a lens of relative aperture f 1.6, as much as 6000 lumens. The lamp consumes 800 W, so that the efficiency is respectively 6 and 7.5 lumens/watt on the screen, compared with 2.5 lumens per watt in the case of a carbon arc. Owing to the heavier instantaneous loading during the pulses the continuum in the spectrum is intensified with respect to the spectral lines, resulting in good colour rendering. Three light flashes of about 2.5 milliseconds duration are emitted per frame. This gives a strikingly flicker-free picture, even when the picture is very bright and wide. Apart from the illumination system proper, the power supply equipment is also discussed. The mercury lamp employed, type SPP 800 W, is a dosed type and was specially developed for pulsed operation in motion-picture projectors. Some particulars of its development are given.

A MOTION-PICTURE PROJECTOR OF SIMPLIFIED DESIGN

by J. J. KOTTE.

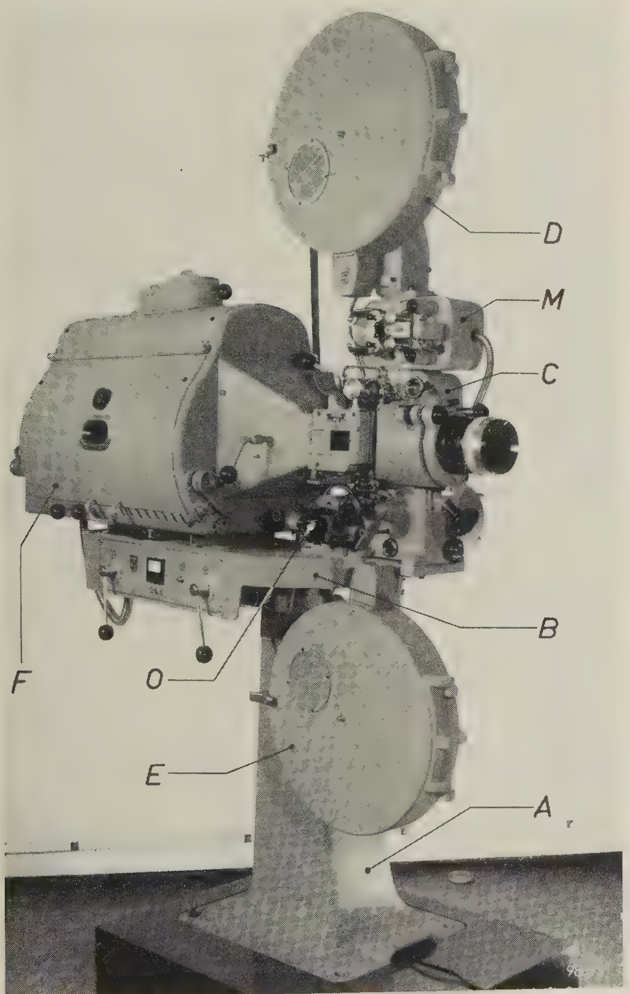
778.554.4:621.327.534.3

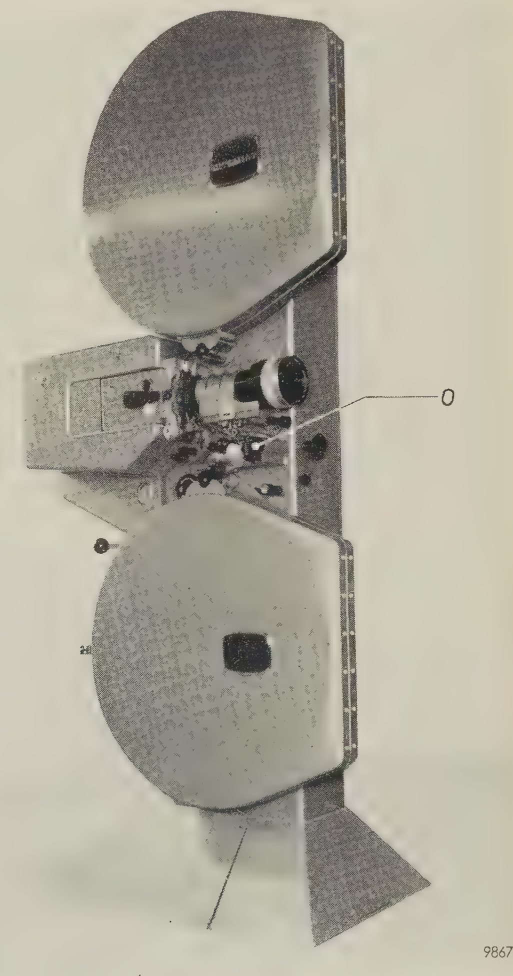
Fresh thought on the problem of how best to meet the demands of modern motion-picture projection has resulted in a projector of new design. It has proved possible to simplify the structure as a whole as well as various details, without, however, making concessions in regard to quality. The projector can be equipped with the pulsed light-source discussed in the preceding article.

Principal design features

The conventional design

Present-day motion-picture projectors are almost invariably built-up from a number of sub-assemblies, each with its own function and as a rule fitting together on accurately machined horizontal faces. An example is the Philips FP 56 projector, shown in *fig. 1a*. This construction has the merit of enabling a projector to be adapted to technical advances by adding new sub-assemblies. When sound films came in, for instance, an optical sound-





a b

Fig. 1. *a*) The Philips projector type FP 56 is an example of the conventional construction of horizontally fitting sub-assemblies. Mounted successively, one upon the other are: the foot A, the mounting platform B, the projection unit C, the magnetic sound-head M, and the upper spool-box D. Below the platform the lower spool-box E and behind the projection unit the lamp house F and the optical sound-head O.

b)The new Philips projector type FP 20. All components concerned with the film path are mounted on a flat vertical panel formed by the front face of a rectangular column. The projector is here equipped with a lamp house containing a pulsed light-source [2]) (it is then designated FP 20 S) and 6000′ spool-boxes. The optical sound-head is mounted at position O.

scanning system was added as a self-contained unit. With the advent of the magnetic sound track some years ago, a new sub-assembly was incorporated between the upper spool-box and the projection unit to make existing projectors meet the new requirements. The flexibility of the sub-assembly construction has thus allowed cinema proprietors to limit the costs of keeping abreast of technical innovations. It is evident, however, that adaptation along these lines does not lead to the most economical and functional design. Each sub-assembly needs its own cast-iron housing or frame, with horizontal faces that all require careful machining. Furthermore, since the path followed by the film must lie exactly in a single (vertical) plane, all these sub-assemblies must be painstakingly "lined up", which takes considerable time and trouble, even for experts [1]).

The new design

In the new projector (fig. 1*b*) a different approach was adopted. The main object was to simplify the design whilst retaining the advantage of flexibility, i.e. the possibility of adding or replacing components to meet the demands of the users. In short, the aim was to preserve the virtues of the sub-assembly layout but to avoid its drawbacks.

To this end, all components concerned with the film path are mounted on a *vertical* panel, thus dispensing with the laborious work of lining-up. The heart of the projector is a column of rectangular cross-section, bent and welded to shape from sheet steel. The column is closed at the top by a welded steel cover to increase the rigidity of the structure. At the bottom, which is open, a base piece gives it the required rigidity. The wide side-panel on which the components are mounted is easy to bring within the specified flatness tolerances. It requires no special machining and the assembly surfaces may even have a coating of paint.

The mounting panel contains all the necessary holes, threaded and otherwise, appropriate to the various versions of the projector. For example, spool-boxes for 600 m (2000 ft) film spools can be mounted, or for 1800 m (6000 ft) spools. The bearing brackets for the spool spindles must then be shifted. In all versions the projector is fitted with an optical sound-head, but if the upper spool-box is moved up 140 mm there is room on the column for a magnetic sound-head too. The newly dev-

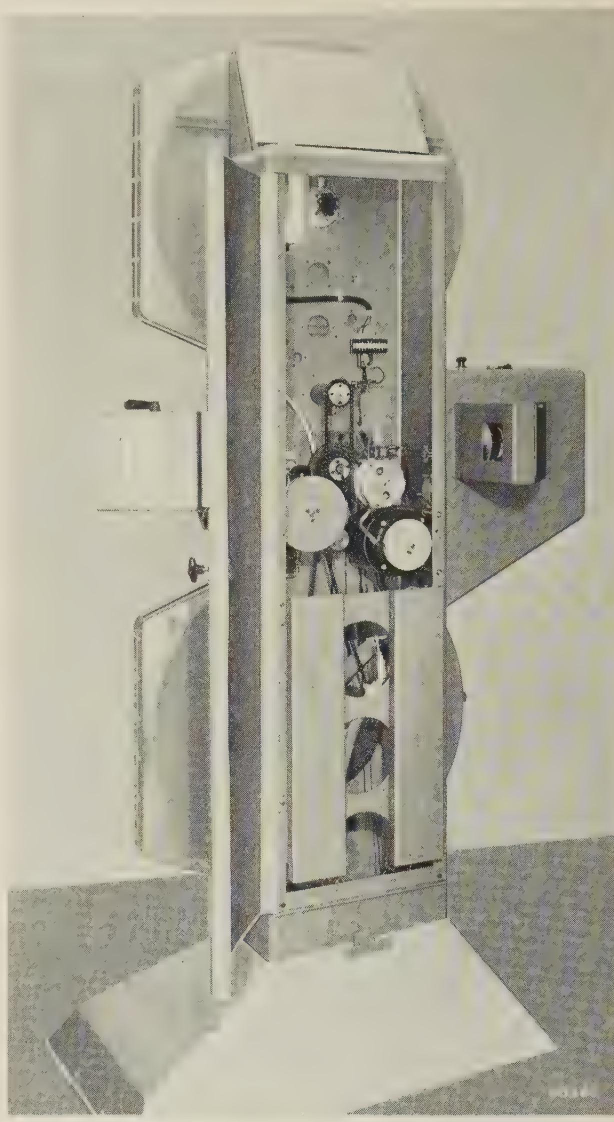


Fig. 3. The interior of the column is accessible through generous openings in the rear wall, closed by a common door. Note the chain-drive transmission system.

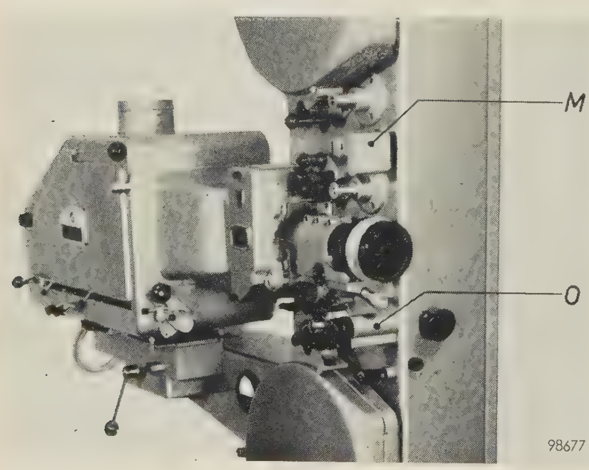


Fig. 2. The new projector equipped with an arc lamp (then designated FP 20), 2000′ spool-boxes and a magnetic sound-head *M* in addition to the optical sound-head *O*.

[1]) If a cinema has to be provided with a new projection system, the installation time is a point of a importance in that it determines the number of performances missed. The time needed to line-up the projectors adds significantly to the total time of installation.

eloped lamp-house with pulsed light-source, discussed in the preceding article [2]), can be attached directly on to the mounting panel. The projector shown in fig. 1*b* is equipped with the new lamp-house and 1800 m spool-boxes, but not with a magnetic sound-head. (The latter is, however, to be seen fitted on the projector in fig. 1 of the preceding article.)

Equipped with a pulsed light-source the projector is designated as type FP 20 S. If the light-source is an arc lamp — as in *fig. 2* — a platform is screwed to the column on which any current type of lamp-house can be mounted. The type designation is then FP 20. In fig. 2 the projector is fitted with a magnetic sound-head and 600 m spool-boxes.

The column construction makes it possible to drive all parts concerned by very simple means, that is by chains. The chains run slowly and silently, and are safely accomodated, free from dust, inside the column (*fig. 3*). In a projector as in fig. 1, on the other hand, two helical gears, two bevel gears and two transmission shafts are required for driving the lower spool alone. To change over from 600 m to 1800 m spools on the new projector, all that is necessary is to shift the bearing brackets for the lower spool spindle and to lengthen the driving chain. In the old construction it is necessary to mount, besides the bigger spool boxes, larger castings and a longer transmission shaft; the film path as well as the transmission shaft then has to be lined up.

The interior of the column is also the ideal housing for the electric wiring. The electrical connections between the various sub-assemblies by means of flexible cables (visible in fig. 1*a*) are thus a thing of the past. Since the column is open at the foot, the projector can be readily connected to the power supply and water main via lines under the floor.

[2]) See previous article in this issue: P. Hoekstra and C. Meyer, Motion-picture projection with a pulsed light-source, Philips tech. Rev. **21**, 73-82, 1959/60.

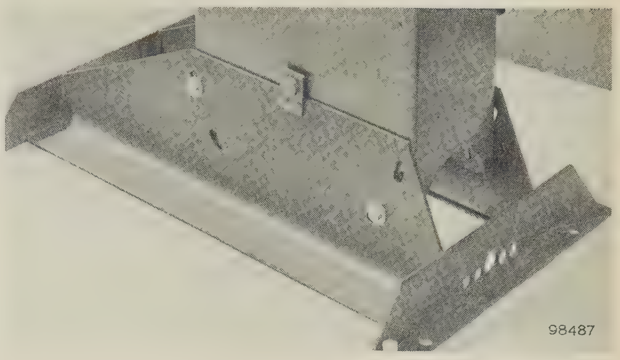


Fig. 4. The projector base with hoods removed.

The foot of the column fits into a base consisting of two angled plates welded to two L-sections to form a frame (*fig. 4*). The column rests on the plates at the protruding ends of a fixed spindle passing crosswise through the foot; the whole column can be tilted around this spindle into the required projection angle and then secured by bolts. The base frame is afterwards covered by a two-piece hood.

New design details

Framing adjustment

Since 35 mm film is provided at either side with four sprocket holes per frame, it is possible that a film may be positioned in the film gate one or two perforation holes too high or too low. It may also

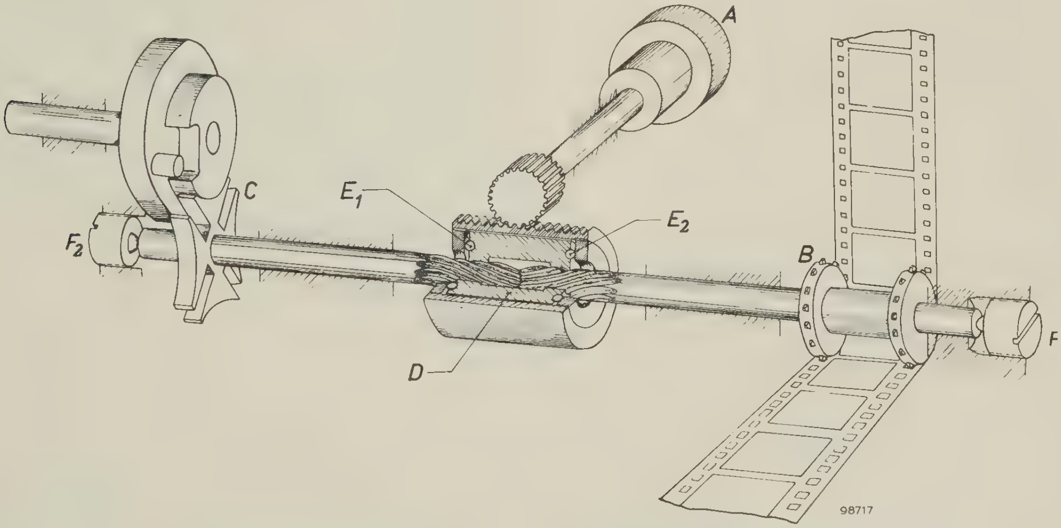


Fig. 5. Principle of the framing device used in the FP 20 projector. *A* framing knob, *B* intermittent sprocket, *C* Maltese cross, *D* coupling sleeve, E_1 and E_2 ball-bearings, F_1 and F_2 hardened thrust bolts.

happen during projection that when a badly framed splice has passed the film gate the black line dividing the frames appears on the projection screen. In order to correct such faults quickly, all 35 mm projectors are fitted with a device for framing adjustment.

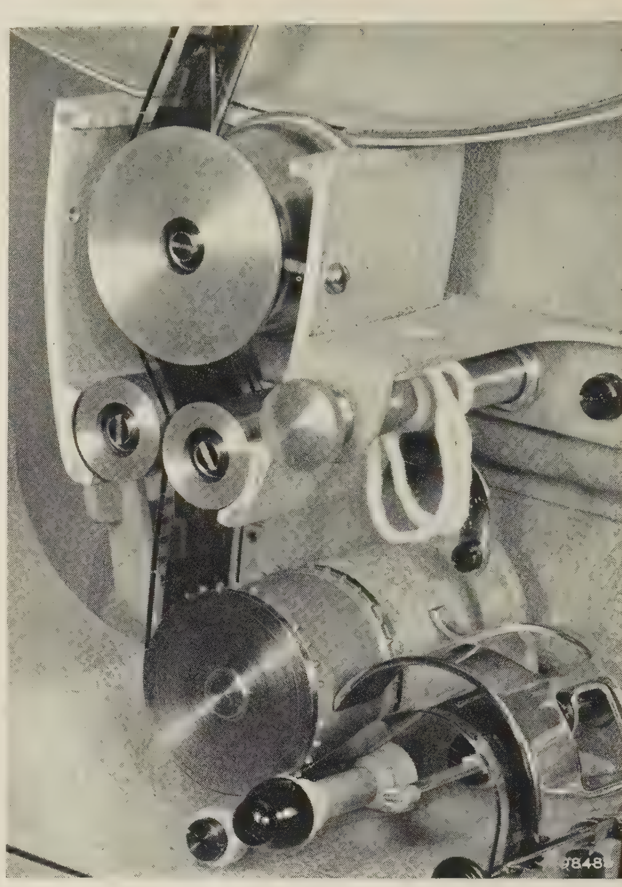
The framing device in the projector under discussion is of new design, the principle of which is illustrated in *fig.* 5. When the framing knob A is turned, the intermittent sprocket B undergoes rotation relative to the Maltese cross C, thereby shifting the film whilst in motion and effecting the necessary correction.

Many projectors in common use, including some Philips types, employ the method of central framing adjustment because of its reliability. Here, too, the intermittent sprocket turns during framing, but since the spindle between the Maltese cross and intermittent sprocket is not divided, the whole Maltese cross mechanism turns too. If no counter-measures are taken, this upsets the mutual adjustment between the frame-shift period and the light-interception by the shutter. A complicated mechanism is required to prevent this happening.

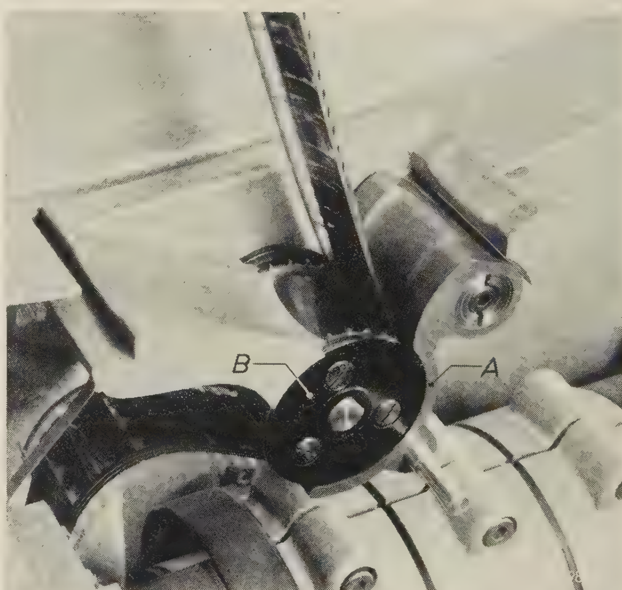
The coupling sleeve D (fig. 5), which is internally splined to mate the coupled ends of the spindle, is an injection-moulded product of nylon. This is an ideal material for the purpose in question, where a sleeve is required that can be shifted along a shaft with absolutely no backlash [3]). The dimensions of the sleeve can quite permissibly be made 1% to 2% smaller than the spindle (with steel-to-steel, a press-fit is obtained with under-dimensioning of only 0.01-0.1%. Initially a good deal of force is needed to shift the sleeve, but in the course of about 24 hours the material "sets" as a result of creep, so that the force required drops to an acceptable level. This force is transmitted to the sleeve via thrust ball-bearings E_1 and E_2 and finally taken up by the hardened thrust bearings F_1 and F_2 at both ends of the divided intermittent spindle. Life tests have shown that no backlash occurs even after intensive use.

Fire traps

The fire traps are another example of simplified design in the new projector. Their purpose is to ensure that, if the film catches fire, the fire will not spread to the spools. The conventional design of a fire trap (at the upper spool-box) can be seen in *fig. 6a.* Upon leaving the feed spool the film passes through a roller fire-trap which is closed at the front by a lid fastened to the spool box (not visible in the photograph). Below the fire trap is a sprocket with two pad-rollers which ensure that the sprocket teeth engage properly in the film perforations. Fig. 6*b* shows the new design in which the pad rollers are replaced by a guide shoe enveloping the sprocket



a



b

Fig. 6. *a*) Illustration of conventional fire-trap design as employed in projector type FP 56.
b) Fire-trap design in the FP 20 projector, composed of guide shoe and sprocket.

[3]) The properties of nylon as an engineering material are discussed e.g. in A. J. Cheney, Designing with nylon, Machine Design, 23rd February 1956, 95-102, and 8th March 1956, 95-99.

over a wide angle, such that shoe and sprocket together constitute at the same time a fire trap. Here too the fire trap is closed by a flat lid attached to the spool cover (not visible in the figure). This design cuts down on components, dispenses with the need for alignment and halves the time taken to thread the film.

Remote control from the auditorium

In large cinemas the screen is so far away from the projectors that the projectionist is unable to focus the picture as sharply as someone nearer the screen. Provision has therefore been made in the new projector for incorporating inside the column a small motor which, via reduction gears, controls the focus adjustment. The motor is operated from a control box set up inside the auditorium. The framing and the sound volume can also be adjusted from this control box. If the projector is equipped with the new pulsed-source lighting system, the box can also be provided with a control for regulating the lamp power [4]).

[4]) See preceding article, page 80.

Summary. Conventional motion-picture projectors are composed of self-contained sub-assemblies which fit together on accurately-machined horizontal faces. A new projector of simpler design is described. All components concerned with the film path are mounted on the flat front panel of a sheet-steel column of rectangular cross-section. This dispenses with the laborious work of lining-up the film path when installing the projector. The front panel contains all holes, threaded and otherwise, required for adapting the projector with the minimum of trouble to individual requirements. The column accomodates a simple and reliable chain-drive transmission system; it is also the ideal housing for the electric wiring. Some other design details are discussed, viz. a framing device and a fire-trap system, both of simplified design.

A SLOTTED LECHER LINE FOR IMPEDANCE MEASUREMENTS IN THE METRIC AND DECIMETRIC WAVE BANDS

by G. SCHIEFER *)

621.317.332.1:621.372.2

In the V.H.F. bands, impedance measurements on balanced components such as aerials, transformers and coupling loops, are usually made with unbalanced (unsymmetrical) test equipment, special fourpoles or "baluns" being inserted to effect the transition from balance to unbalance. Generally speaking such inserted devices are open to the following objections: either they have a very narrow frequency band and must accordingly be matched with the utmost accuracy to each test frequency (e.g. half-wave stubs), or they have a broad frequency band but at the same time such complex four-pole properties that impedance measurements are only possible if the precision required is not very high. For accurately measuring balanced impedances (in particular low-loss reactances) within a wide range of frequencies we have therefore designed a slotted lecher line on which the standing wave pattern can be detected in the familiar way with a travelling probe and thus the connected impedance derived.

The design of such a slotted line is governed primarily by the following considerations:

a) The line must be screened to minimize interference due to "hand effect" and radiation pick-up (e.g. in aerial measurements).

b) The shape of the cross-section must be such that the characteristic impedance of the line may be calculated beforehand from the geometry.

c) The characteristic impedance must be affected as little as possible by slight errors in the position of the conductors.

d) It should be possible to lengthen the line at the object end with ordinary lecher wires, whether screened or not, without causing reflections at the junction as a result of cross-sectional disparities.

e) The useful length of the line must be greater than half the longest-occurring wavelength.

Conditions *a*) to *d*) point in the direction of a screened lecher line with inner conductors and screening of circular cross-section (*fig. 1*). The characteristic impedance of such a line may be calculated very accurately, and at a given ratio d/D of the diameters it shows a maximum when the centre-to-centre distance a of the inner conductors is approximately half the inside diameter D of the screen. In that case the electrical properties of the line are insensitive to small errors in the position of the inner conductors. Since the characteristic impedance did not have to have any specified value, $d = \frac{1}{4}D$ was decided upon. This leaves a wide choice for d and D amongst the brass tubing commercially available. Moreover the damping of a screened lecher line is just about minimum with this ratio of diameters. Calculated according to Sommer [1]), the characteristic impedance proves to be 104.7 ohms; allowing for the narrow lengthwise slot (see below) the value is 105 ohms. (A round figure of e.g. 100 ohms would have simplified measurements, but would have led to an unfavourable value of d/D.)

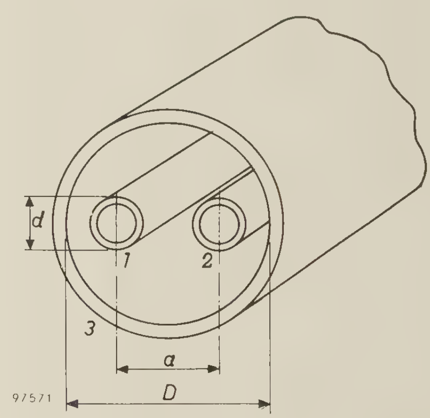


Fig. 1. Lecher line *1-2* with outer conductor (screen) *3*. Relations between dimensions: $a = \frac{1}{2}D$, $d = \frac{1}{4}D$.

In order to carry out measurements in the whole of V.H.F. band II (87.5-100 Mc/s, maximum wavelength 3.45 m), the line is made about 2 metres long; see point *e*) above. This makes the lowest measuring frequency about 80 Mc/s. Of course, measurements may also be extended to lower frequencies by connecting additional sections of line. The upper frequency limit of the line is set by the occurrence of waveguide modes of oscillation which, however, appear only at frequencies above 1000 Mc/s.

The line (*fig. 2*) consists of a rigid brass tube (inside diameter 48 mm, outside diameter 60 mm) which serves as the screening conductor, and two inner conductors, also of brass tubing (10 mm inside and 12 mm outside diameter). The inner conductors are held by supports mounted at distances of about

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1) F. Sommer, Die Berechnung der Kapazitäten bei Kabeln mit einfachem Querschnitt, Elektr. Nachr.-Techn. 17, 281-294, 1940.

40 cm apart; each support consists of two 4 mm bolts of "Teflon" (polytetrafluorethylene), which are screwed at right-angles to each other into the inner conductors, their heads being locked in the outside conductor. At the line input the support is a disc of "Trolitul", which is permissible since reflections are not critical at this location. The screen also serves as a guide rail for the carriage carrying the probe-detector; the latter, which we shall discuss presently, projects into the line through a 5 mm-wide slot cut into the screen along the whole of its length.

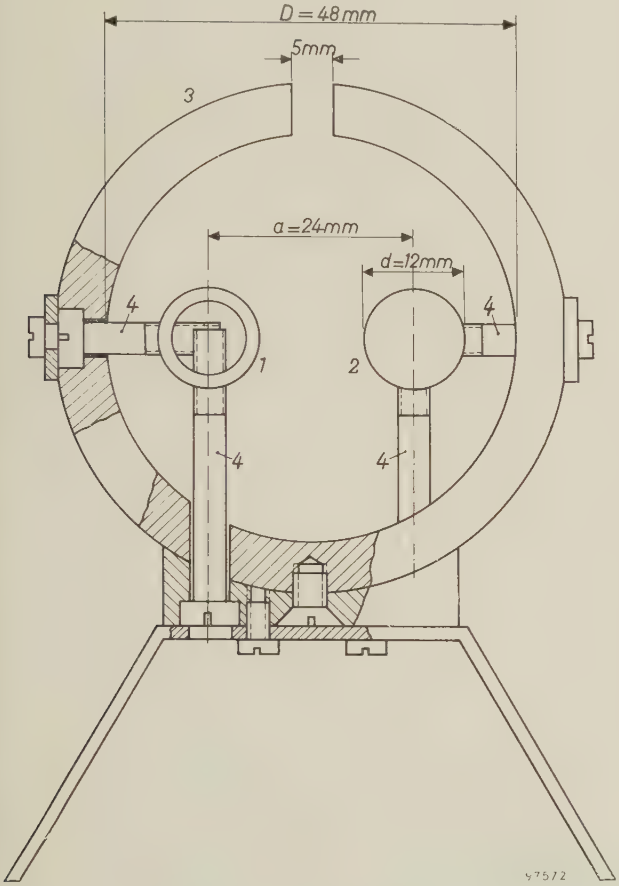

Fig. 2. Cross-sectional view of the lecher line. *1* and *2* conductors of brass tubing, supported by bolts *4* of "Teflon". *3* screen of brass tubing with slot for probe.

As fig. 2 shows, this design makes it easy to adjust the horizontal and vertical alignment of the inner conductors; half the space inside the screen in which the probe moves is completely free of interfering elements. The effect of the supports on the electrical properties of the line is thereby negligible. This is due in large measure to the low dielectric constant of the plastic insulation material used ($\varepsilon_r = 2$). The mechanical properties of the material have also proved satisfactory; after six months' use there was no sign whatsoever of creep deformation.

The line is fitted at both ends with symmetrical connection flanges (see fig. 4) with plug-sockets for the inner conductors.

Special attention was paid to the probe-detector. With all balanced line systems it is necessary in practice to take into account the occurrence of asymmetrical waves. These arise even if there is only a slight unbalance or asymmetry somewhere in the transmission system, and if resonance conditions are favourable they may be exceptionally severe. In the case of a screened lecher line the danger is particularly great, for it also possess good transmission properties as a *coaxial* system, the inner conductors then being in phase with each other and the screen in antiphase.

Where asymmetrical waves arise as a result of unbalance in the test object itself, they inevitably result in spurious measurements. It is easy to see that the balanced impedance of a two-terminal network can only be measured properly by means of a three-conductor system if the third conductor (the outer one) remains neutral. Such errors of measurement can therefore be avoided only by ensuring that the test objects are accurately balanced electrically, which in most cases also means geometrically symmetrical.

Where, however, asymmetrical waves arise as a result of unbalance preceding the test object — i.e. mainly in consequence of an unbalanced supply voltage — they can be prevented from affecting the result of the measurement if a probe be used that is insensitive to these waves. With this in mind we first made a series of experiments with tuned probes, which seemed to us favourable because of their high sensitivity and their suppression of higher harmonics. We found, however, that neither with electrical nor with magnetic coupling was it possible, at reasonable cost, to make the tuning device sufficiently balanced to suppress the indication of unbalanced waves in the whole frequency band. In this respect non-tuned probes were better, but they were not sensitive enough. Satisfactory results were finally obtained by introducing the detector diode of the probe directly into the radio-frequency field of the two inner conductors. In this way we dispense with all connections in the R.F. circuit of the probe that might give rise to frequency-dependence and unbalance. At the same time we have a probe that is sensitive enough and relatively easy to balance in the whole frequency band.

The final arrangement is shown schematically in *fig. 3*. The connection wires of a miniature germanium diode, type OA95, form a dipole located directly in the field between the two inner conductors.

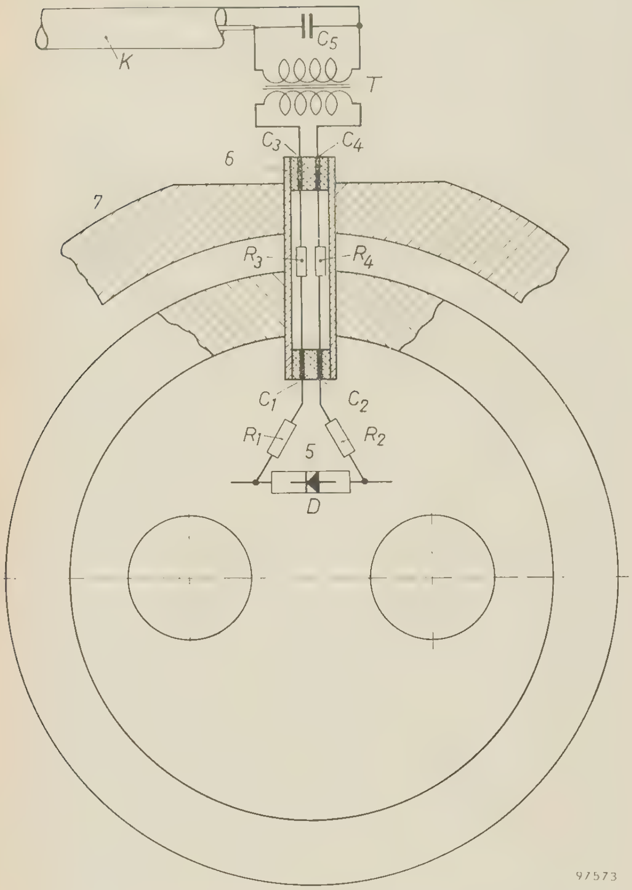

Fig. 3. Probe arrangement. The probe proper *5* is fixed by means of tube *6* to the carriage *7* which travels along the line. *D* miniature germanium diode OA95. R_1-R_2 miniature resistors constituting the high-frequency load for the diode. The balanced lead-through capacitors C_1-C_2 and C_3-C_4, together with resistors R_3-R_4, form a low-pass filter. *T* transformer tuned to 1000 c/s. C_5 matching capacitor at low-frequency side. *K* cable to probe amplifier.

The current is taken off via two symmetrically connected miniature resistors, which also act as the R.F. load for the diode. The high frequency is filtered-out by a balanced low-pass filter, consisting of special lead-through capacitors and resistors that form an intrinsic part of the tube by which the probe is introduced through the slot.

To make the indication as sensitive as possible the high-frequency supply voltage is modulated in amplitude by 1000 c/s, and a transformer tuned to 1000 c/s is incorporated in the low-frequency part of the probe for the purpose of matching to the unbalanced input of the probe amplifier. At a bandwidth of 8 c/s this specially designed amplifier is so sensitive that a low-frequency voltage of 0.5 μF can still be read-off with certainty.

In this way the total sensitivity is such that, at a high-frequency supply voltage of 5 V (across 105 ohms) and a standing-wave ratio of some hundreds, the voltage minima can still be readily detected. This is just about the limit that can be reached, seeing that standing-wave ratios of this order of magnitude are caused by the natural damping of the line itself (when short-circuited). However, since the probe has a wide frequency-band, such measurements call for a high-frequency supply voltage substantially free from higher harmonics.

The probe is mechanically guided by a carriage, as mentioned, which travels smoothly along the screen on six ball bearings. Also mounted on the carriage are a device for reading the length coordinate and a box containing the matching trans-

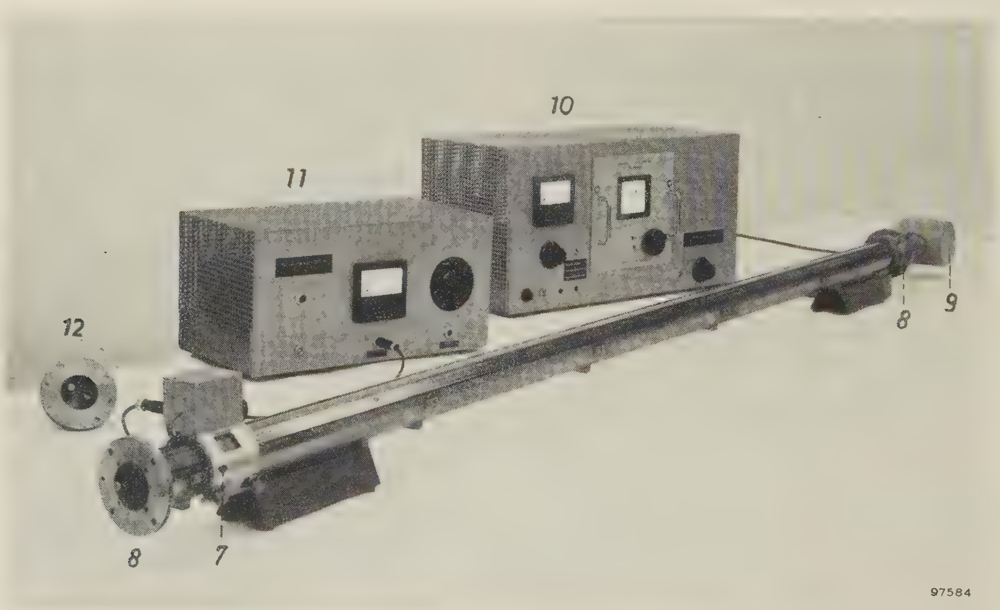

Fig. 4. Complete equipment. In the foreground the transmission line with connection flanges *8* and balun *9*. Left, on the line, the probe carriage *7* travelling on ball bearings. At the back the generator *10*, the probe amplifier *11* and a matched termination impedance *12* of 105 ohms.

former, with a socket for connecting the cable to the probe amplifier. After careful alignment of the inner conductors and proper positioning of the probe, variations in the indication as a result of errors in the parallel travel of the carriage with respect to the inner conductors are less than 2%.

Fig. 4 shows the line, complete with the high-frequency generator and the probe amplifier. The principal data are given below. The apparatus is at present used in the frequency range from 80 to 300 Mc/s.

Principal data of the balanced slotted line

Line

Characteristic impedance .	105 ohms $\pm$ 0.5%.
Natural damping	at 100 Mc/s: 9×10^{-6} Np/cm at 300 Mc/s: 16×10^{-6} Np/cm
Useful length:	1891 mm.

Probe

Variation in sensitivity between 80 and 300 Mc/s . .	$< 2:1$.
Disturbance introduced by probe in the R.F. field, in maximum of standing wave	< 1%.
Diode characteristic: . . .	quadratic to a low-frequency indication of approx. 1 mV.

Longitudinal uniformity: mechanical tolerances of the line and probe guide system, and inhomogeneities such as supports and connections, give rise to non-uniformities along the length of the line. Their effect on the measurement of voltage and length is determined as follows. With a matched termination, consisting of a balanced resistance of 105 ohms, the indicated voltage over the total length of the line varies by a maximum of 2%. If the line is terminated by a shorting plunger, the voltage nodes shift by $\pm$ 1 mm max. The absolute accuracy in impedance measurements can be derived from these data from case to case.

High-frequency generator

Frequency range	80-300 Mc/s.
Power output	1 W in unbalanced resistance of 60 ohms.
Higher harmonics.	< 1%.
Modulation frequency . . .	1000 c/s $\pm$ 1 c/s.
Modulation depth.	> 80%.

The high-frequency energy is conducted to the test line via a broad-band balun with conical transition.

Probe amplifier

Frequency band	1000 c/s $\pm$ 4 c/s.
Input impedance	100 kΩ.
Measuring ranges	12 ranges with full scale deflections of 3 μV to 1 V.
Noise voltage	< 0.15 μV.

Accessories

For connecting test objects to the line, extension pieces are available and also adaptors for changing over to smaller cross-sections. Careful construction and correction of the supports ensure that these accessories cause no measurable mismatch or unbalance errors.

Summary. For impedance measurements on balanced objects in the V.H.F. bands (80-300 Mc/s), a balanced, screened transmission line about 2 metres long has been designed in the Philips laboratory at Aachen. The characteristic impedance is approx. 105 ohms. The probe is insensitive to unsymmetrical waves, the detector diode (a miniature germanium diode OA95) being introduced directly into the R.F. field inside the line. The high-frequency supply voltage is modulated in amplitude at 1000 c/s. The total sensitivity in such that, at a high-frequency supply voltage of 5 V and a standing wave ratio of some hundreds, the voltage minima can still be accurately measured.

AN 8 mm HIGH-RESOLUTION RADAR INSTALLATION

by J. M. G. SEPPEN *) and J. VERSTRATEN **).

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The display on a radar screen of the PPI type (plan position indicator) represents an "echo map" of the area scanned by the aerial. With relatively long waves, objects can be "seen" in this way which are far beyond the optical range. Radar is also used, however (with shorter waves), to detect and locate objects within the optical range, for darkness and fog present no obstacles to radio waves.

An area viewed by direct optical means obviously contains many more details than the radar display, which is merely a very rough indication. The degree to which objects can be distinguished, i.e. the resolution of the apparatus, sets a limit to the usefulness of radar for various purposes. N.V. Philips Telecommunicatie Industrie have now designed a radar installation, type 8 GR 250, which operates in the 8 mm wave range and has a very high resolution. The article below gives a description of this apparatus together with some theoretical considerations underlying the design.

Introduction

The 3 cm and 10 cm wavelengths have long been used for navigational radar with excellent results where fairly long ranges are concerned. For navigation within a restricted area, however, the apparatus is required to have a very high resolution, which is difficult to achieve at these wavelengths. In harbours and narrow waters, for example, navigators not only require accurate knowledge of the distances to the numerous obstacles, they also wish to see the manoeuvres being carried out by other ships. The latter can be deduced if the true shape of the ships is discernible on the radar screen ("ship-shape" radar).

A resolution as high as this is only possible with a radar set built to operate at an even shorter wavelength. N.V. Philips Telecommunicatie Industrie have designed such an installation, type 8 GR 250, working on a wavelength of 8.6 mm. Apart from its usefulness on ships frequently in narrow or busy waters, or on large ships as auxiliary and harbour radar, it can also be used in airports for controlling traffic on runways and aprons (ASMI-radar, Airfield Surface Movement Indicator [1]).

Principles of radar

Since the subject of radar [2]) has never been dealt with at any length in this journal, we shall begin with a brief description of its principles.

The radar station sends out radio-frequency pulses which, being reflected from the objects in their path, give rise to echo signals which are picked up by the radar receiving system and displayed (for example) on the screen of a PPI tube (Plan Position Indicator). The echoes then trace out on the screen a "map" of the area scanned, the objects appearing on the screen as luminous spots on a dark background. We shall now examine in greater detail how such a system works, with reference to the block diagram of the 8 mm radar installation given in *fig. 1*.

Periodic high-voltage pulses from a modulator are applied to an 8 mm magnetron which thereupon delivers high-frequency signals of extremely short duration. The repetition frequency is controlled by a pulse generator which supplies the synchronizing signals. The high-frequency pulses delivered by the magnetron (wave trains) are conducted via a waveguide to the antenna. This consists of a parabolic reflector at the focal point of which the waveguide is flared out to form the "feeder" (horn). The wave trains are transmitted by the reflector in a narrow beam. If they encounter an obstacle in their path, energy is reflected (i.e. scattered) in all directions. The signals reflected back to the radar station are picked up by the receiving antenna, which is mounted parallel with the transmitting antenna. A superheterodyne receiver, containing a mixer stage and a klystron as local oscillator, converts the echo signals into pulses of lower frequency (intermediate frequency, in this case 90 Mc/s). These are amplified, detected, again amplified in a video amplifier and then applied to the cathode-ray tube. A synchronizing pulse obtained from the magnetron ensures that the time base of the CRT starts at the same

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**) Formerly with N.V. Philips' Telecommunicatie-Industrie.

[1]) This 8 mm radar equipment has already been described by the authors in T. Ned. Radiogenootschap **23**, 17-32, 1958 (No. 1) and in Philips Telecomm. Rev. **20**, 5-15, 1958, (No. 1).

[2]) Coined from "*ra*dio *d*etection *a*nd *r*anging". See e.g. Louis N. Ridenour, Radar system engineering, Radiation Laboratory Series, No. 1, McGraw-Hill, New York 1947.

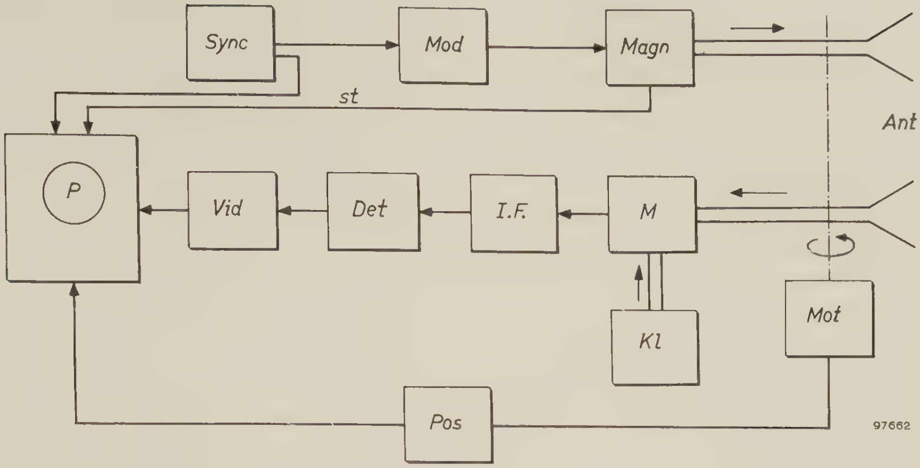

Figure 1. Block diagram of the 8 mm radar installation. *Magn* = magnetron, *Mod* = modulator, *Sync* = synchronizing pulse generator, *Ant* = rotating antennae, *Kl* = klystron, *M* = mixer, *I.F.* = intermediate frequency amplifier, *Det* = detector, *Vid* = video amplifier, *P* = PPI unit, *Mot* = motor for driving the antennae, *Pos* = position-coupling of antennae and time base; *st* denotes the starting pulse delivered by the magnetron to the time base circuit.

moment as the transmitted pulse. The electron beam is magnetically deflected in the radial direction by a coil made to rotate around the neck of the tube in synchronism with the antennae, which rotate about a vertical axis. The time base of the CRT begins in the middle of the PPI screen and runs radially to the edge in a direction corresponding to that in which the antennae are pointing. The received pulse is now used to modulate the intensity of the electron beam, which is normally just below the threshold of illumination. In this way a map of the swept area is traced out on the PPI, echoes from objects farther away taking proportionately longer to reach the receiver and thus producing a luminous spot farther away from the centre of the PPI screen. *Figs. 2* and *3* give some idea of the accuracy with which the PPI of the 8 mm radar installation displays the surroundings.

Fig. 2

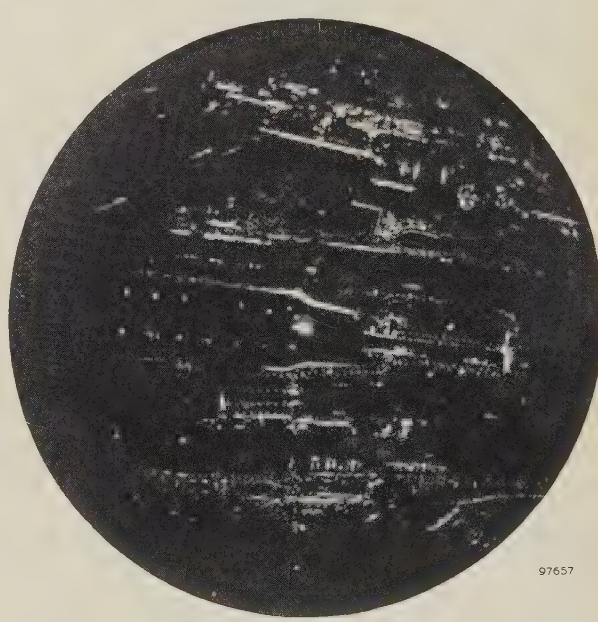

Fig. 3

Fig. 2. Map of Ymuiden docks, scale 1 : 25 000.

Fig. 3. Radar display of Ymuiden docks obtained with the 8 mm radar installation 8 GR 250. (Screen coverage set to 2 km diameter.)

The operation of radar thus depends among other things on the following three facts [3]):

1) The velocity of propagation of electromagnetic waves is constant, so that the time taken for a pulse to travel to an object and back is a direct measure of the distance to the object.
2) The transmitter is able to generate pulses of high power and extremely short duration. In the interval between these pulses the receiver has the opportunity to register the echoes.
3) The use of very short wavelengths (in the centimetre or millimetre range) makes it possible to produce a very narrow beam of radiation with an antenna of moderate size, so that the pulses are transmitted and received in a well-defined direction.

Effect of wavelength on the properties of a radar system

The foregoing indicates that the properties of a radar system are largely determined by the wavelength. In the following we shall discuss the effect of wavelength on the resolution (discrimination) of the system and on the range.

Antenna

As we have seen, the antenna is a parabolic reflector fed with RF energy via a horn at the focal point. A sharp parallel beam is not produced; owing to diffraction phenomena it fans out into a more or less conical pencil with its origin at the centre-point of the antenna. At the edge of this pencil the field-strength falls off fairly rapidly to zero.

The apex angle of the pencil in the horizontal plane is conventionally defined as the angular width ϑ_h between the directions in the beam in which the intensity of the radiation falls to half the maximum intensity. This beam width (in radians) is approximately given by the formula:

$$\vartheta_\mathrm{h} = \lambda/l_\mathrm{h}, \quad . \; . \; . \; . \; . \; . \quad (1a)$$

where λ is the wavelength and l_h the linear dimension of the antenna in the horizontal plane. In the same way one can also define a beam width in the vertical plane (see *fig. 4*):

$$\vartheta_\mathrm{v} = \lambda/l_\mathrm{v}\,. \quad . \; . \; . \; . \; . \; . \quad (1b)$$

For a measure of the directivity of an antenna, the radiation in a certain direction is compared with that of a hypothetical isotropic source, i.e. one which transmits energy equally in all directions; if this source radiates a total power P_0, a power $P_0/4\pi R^2$ will pass through unit area at a distance R. With the aid of a reflector the intensity in a given direction can be increased by a factor G. The antenna power gain or directive gain is taken as the maximum value of this factor, that is, along the axis of the beam. It is given by the formula:

$$G_0 = 4\pi A/\lambda^2, \quad . \; . \; . \; . \; . \; . \quad (2)$$

where A is the effective area of the antenna (approximately 0.7 times the actual area). The way in which this formula is arrived at can be understood by regarding the solid angle as the product of the beam widths ϑ_h and ϑ_v (see equations $1a,b$) and by comparing this solid angle with the solid angle 4π in which the isotropic source radiates; hence $G_0 = 4\pi/\vartheta_\mathrm{h}\vartheta_\mathrm{v}$. From (2) it can be seen that a shorter wavelength results in an increased gain. The effect of this on the range of the radar installation appears in the radar equation discussed below.

The radar range equation

If the power radiated is P_0, the signal power received back at the radar station is given by

$$P = \left(G_0 \frac{P_0}{4\pi R^2}\right)\left(\frac{\sigma}{4\pi R^2}\right)A\,. \quad . \; . \; . \quad (3)$$

This equation assumes propagation in free space, no account being taken of losses due to atmospheric effects, etc. The first factor comprises the abovementioned transmitted power beamed by the antenna and incident on an object at a distance R. The object scatters the incident energy, and a small fraction returns in the direction of the radar station. This fraction is expressed in the second factor, where σ is the effective reflecting area of the object.

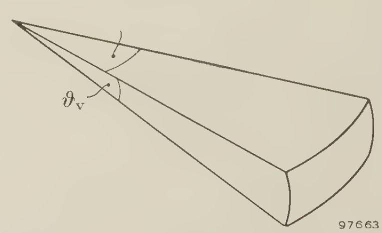

Fig. 4. Illustrating the horizontal and vertical beam widths

Taking for P the value P_min, which is the minimum signal detectable by the receiver, we can write for the range R_max of the radar system:

$$\left.\begin{aligned} R_\mathrm{max} &= H \sqrt[4]{\frac{P_0}{P_\mathrm{min}}} \sqrt[4]{\frac{\sigma}{4\pi}}, \\ \text{where} \quad & \\ H &= \sqrt{\frac{G\lambda}{4\pi}} = \sqrt{\frac{\lambda}{\vartheta_\mathrm{h}\vartheta_\mathrm{v}}} = \sqrt{\frac{A}{\lambda}}\,. \end{aligned}\right\} \quad . \; . \quad (4)$$

[3]) We are concerned here solely with pulse radar. Other systems exist, but are not relevant in this connection.

From this "radar equation" we can draw the following conclusions.

a) Assuming the antenna dimensions, peak pulse power and minimum detectable signal to be kept constant, the range in free space is inversely proportional to $\sqrt{\lambda}$, i.e. proportional to $\sqrt{f}$, the root of the frequency. This would argue in favour of making the frequency as high as possible, were it not that electromagnetic-wave propagation in the atmosphere becomes, in general, poorer with increasing frequency. We shall return to this presently.

b) If the directive gain, and hence the beam width, of the antenna be kept constant — which implies that the linear dimensions of the antenna must change proportionately with the wavelength — then the range is proportional to $\sqrt{\lambda}$.

c) If the range is to be kept constant, assuming the properties of transmitter and receiver to be constant, then A/λ must remain constant; in other words, the linear dimensions of the antenna must be proportional to $\sqrt{\lambda}$.

Applying the above considerations to the transition from a 3 cm to an 8 mm radar system (and assuming for convenience that the ratio of the wavelengths is 4), we see the following. The beam width being the same, the range is reduced by half. The antenna area becomes 16 times smaller. Compensation of the loss of range by increasing the power will entail at least a 16 times higher power. If we wish to keep the range constant, the antenna of the 8 mm system must be made only 4 times smaller in area, i.e. half the linear size. It is then still necessary to compensate for a loss of range due to atmospheric effects.

Resolution

A distinction is made between tangential and radial resolution. On the PPI and over the area around the radar station we imagine there to be a system of polar coordinates with the origin at the radar station. The *radial* resolution is determined by the length τ of the pulse sent out by the magnetron. The transit time of the pulse from the antenna to an object at a distance R and back is given by $t = 2R/c$, where c is the velocity of light. Two objects, separated radially from each other by a distance ΔR, can only be distinguished if the difference in the transit time of the pulses, $2\Delta R/c$, is greater than the pulse length τ. This minimum distance, which is equal to $c\tau/2$, is the radial resolution, or discrimination, of the radar system. It is evidently desirable to have the shortest possible pulse length τ. This cannot be indefinitely shortened, however, since the magnetron requires a number of cycles before it gets up to peak power. This implies that at shorter wavelengths pulses of shorter duration can be generated, thus improving the radial resolution. With the 8 GR 250 the pulse length τ is 0.02 μsec, which corresponds to a radial resolution of 3 metres. (We disregard here various contingent factors affecting the resolution.)

The *tangential* resolution is given by the product of the horizontal beam-width ϑ_h and the distance R to the antenna: $R\vartheta_h = R\lambda/l_h$. In order to improve tangential resolution we can therefore either make the antenna larger or the wavelength shorter. With the 8 GR 250 the beam width is approximately 0.3°, and the tangential resolution at a distance of 600 metres approximately 3 metres.

A limitation set to the resolution of a radar system is the finite size of the luminous spot on the cathode-ray tube screen. On the PPI a "map" of the scanned area is reproduced. It is useless if the objects to be discriminated by radar are such that their screen image would be smaller than the luminous spot produced on the screen by the electron beam. In practice the image on the PPI is displayed at a scale adjustable in a number of steps. The largest scale corresponds to the smallest area displayed which, in the 8 GR 250, is a circle having a radius of about 500 metres. On the next scale the radius is about 1000 metres, and so on. The limiting effect of spot size is obviously least for the smallest area. With the 8 GR 250 the various parameters have been so selected as to achieve in the smallest areas the best possible compromise between the resolution of the radar system and that of the cathode-ray tube.

Pulse repetition frequency

The choice of the pulse repetition frequency F is also dependent on the wavelength used. This frequency has to be chosen between certain limiting values.

The maximum value is determined by the following factors.

a) The range R_{max} of the radar system. Considering that each transmitted pulse must be able to travel the maximum distance (to the target and back) before the next pulse is transmitted, the maximum repetition frequency is given by

$$F_{max} = \frac{1}{\frac{4}{3}\,t_{max}} = \frac{3}{4}\,\frac{c}{2R_{max}}. \quad . \quad . \quad (5)$$

The correction factor $\frac{3}{4}$ allows approximately for the flyback time of the cathode-ray tube sweep.

b) The maximum average power W_0 delivered by the magnetron. This imposes the condition:

$$F_{\max}\,\tau P_0 = W_0 . \quad \ldots . \quad (6)$$

The minimum repetition frequency is governed by the speed at which the antenna rotates and by the horizontal beam-width ϑ_h. Since there must be at least one transmitted pulse per angular displacement ϑ_h of the antenna, it follows that

$$F_{\min} = \frac{2\pi N}{60\,\vartheta_h}, \quad \ldots\ldots \quad (7)$$

where N is the number of antenna revolutions per minute. In order to be able to distinguish weak echoes on the screen from the random fluctuations caused by receiver noise, the pulse repetition frequency is always at least several times higher than $F_{\min}$. The antenna then scans each perceptible object with more than one pulse at a time.

With the aid of formulae (4) and (1) we can conclude from the above that, where the antenna dimensions are constant, $F_{\max}$ is proportional to $\sqrt{\lambda}$, and $F_{\min}$ inversely proportional to λ. A shorter wavelength thus means a lower $F_{\max}$ and a higher $F_{\min}$. In the choice of F the value of $F_{\min}$ is of more importance in as much as the number of pulses per observed object has a very marked influence on the minimum detectable signal $P_{\min}$.

Since the 8 GR 250 equipment is especially intended for short-range use, e.g. for surface movement indication on airfields and for navigation in harbours and narrow waterways, a high speed of antenna revolution is evidently desirable, for at distances of a few hundred metres the angular velocities at which objects can change their position with respect to the radar post can be quite considerable. For this reason, and also because of the short wavelength used, $F_{\min}$ had to be fairly high. This led to the choice of $F = 5000$ c/s.

Information capacity

In the above we have indicated how the properties of a radar system depend on the wavelength used. We have seen, among other things, that the resolution and theoretically the range too (that is, neglecting absorption) of the system increase with increasing frequency. We shall now consider the rate at which radar information can be collected, i.e. the information capacity. This is a more general indication of the performance of the system than range and resolution. With the aid of the foregoing considerations we shall arrive at a general formula with which we can ascertain the effect which various quantities, in particular the frequency, have on the information capacity of the system.

We shall first determine the number of observable objects (see *fig. 5*).

No matter how small an object is, it cannot be reproduced smaller than $c\tau/2$ in the radial direction or smaller than ϑ_h in the tangential direction. The maximum number of objects observable within a radius equal to the range $R_{\max}$ (defined for objects with a given reflecting area σ) is therefore:

$$n = \frac{2\pi}{\vartheta_h}\,\frac{R_{\max}}{c\tau/2} . \quad \ldots\ldots\ldots \quad (8)$$

According to information theory we should next ascertain the number of observable states to which one object can give rise. Depending upon its distance, size, etc., an object can return signals to the receiver that vary enormously in strength. In practice, however, this variation is virtually not perceptible in the display (particularly not on the PPI). We can therefore simply say that the number of perceptible states of an object is equal to two, i.e. present or absent — or, more exactly, the state either does or does not give rise to a reflected power at the receiver in excess of the minimum detectable power. With two observable states for each of n objects the total quantity of information I is equal to n bits.

For each complete revolution of the aerial the radar system can thus deal with an amount of information I as given by (8). The information capacity C is the amount of information that can be handled per unit time. If N be the number of antenna revolutions per minute, then

$$C = \frac{IN}{60} = \frac{2\pi N R_{\max}}{\vartheta_h\,\tau \times 30\,c} . \quad \ldots\ldots \quad (9)$$

Inserting the value of $R_{\max}$ given by (4), with $H = \sqrt{\lambda/\vartheta_h\vartheta_v}$, we find:

$$C \propto \frac{N\lambda^{\frac{1}{2}}\,P_0^{\frac{1}{4}}}{\tau\vartheta_h^{\frac{3}{2}}\,\vartheta_v^{\frac{1}{2}}\,P_{\min}^{\frac{1}{4}}} . \quad \ldots\ldots\ldots \quad (10)$$

We now eliminate from this formula the two variables $P_{\min}$ and τ. The minimum detectable signal $P_{\min}$ can be put proportional to the bandwidth B, and since $B = (1 \text{ to } 2)/\tau$, we have:

$$P_{\min} \propto \frac{1}{\tau} .$$

As is clear from (10), to get the best C it is desirable to make the pulse length τ as short as possible. Since the minimum pulse length corresponds to a certain number of high-frequency oscillations of the magnetron (for both build-up and full power of the pulse) we can obviously say that the minimum obtainable pulse length is approximately proportional to the wavelength:

$$\tau_{\min} \propto \lambda \propto \frac{1}{f} .$$

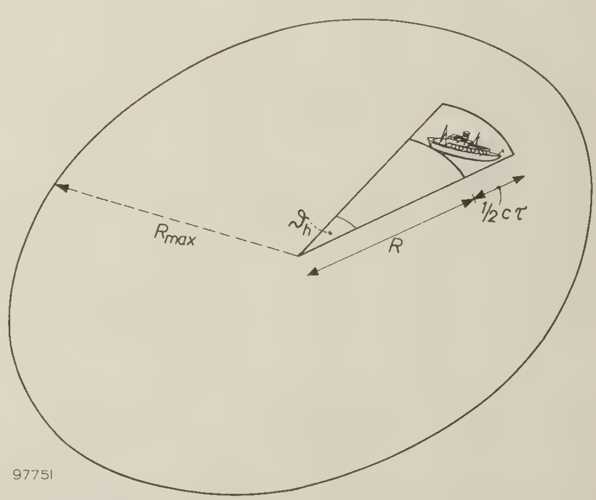

Fig. 5. Determination of the number of objects observabl- with a radar system.

This makes the information capacity:

$$C \propto \frac{N f^{\frac{1}{4}} P_0^{\frac{1}{4}}}{\vartheta_h^{\frac{3}{2}} \vartheta_v^{\frac{1}{2}}}. \quad \ldots \ldots \quad (11)$$

From this we conclude that if we increase the frequency and reduce the antenna dimensions so as to keep to beam-width constant, the information capacity increases in accordance with the fourth root of the frequency.

Assuming constant antenna dimensions, l_h and l_v, we can write the formula somewhat differently. We substitute:

$$\vartheta_h \propto \frac{\lambda}{l_h} \propto \frac{1}{f l_h} \quad \text{and} \quad \vartheta_v \propto \frac{\lambda}{l_v} \propto \frac{1}{f l_v}.$$

The information capacity formula then becomes:

$$C \propto N l_h^{\frac{3}{2}} l_v^{\frac{1}{2}} f^{\frac{9}{4}} P_0^{\frac{1}{4}}. \quad \ldots \ldots \quad (12)$$

This leads to a second conclusion, namely that for constant antenna dimensions the information capacity increases with the frequency to the power of nine fourths.

We may be inclined to conclude that increasing the speed of revolution N of the antenna would increase the information capacity. As indicated by formulae (5), (6) and (7), an increase of N is associated with an increase in the minimum required pulse repetition frequency F_{min}, whereas it is necessary to remain under the maximum value F_{max} corresponding to the maximum average power output of the magnetron. A higher C as a result of increasing N is thus only possible within narrow limits. With regard to (12) it must also be remembered that a higher frequency implies according to (1) a narrower antenna beam, which in turn implies in accordance with (7) that the pulse repetition frequency must also be increased.

Choice of wavelength in relation to atmospheric conditions

Not every wavelength in the millimetre range is suitable for the purposes of radar. The reason is that, owing to atmospheric absorption, attenuation in this range is much greater than in the centimetre range. Closer examination shows that there are various reasons for this, such as absorption by oxygen and water vapour, and attenuation by particles of water in the form of rain, mist, clouds, etc.

As regards the first of these causes, oxygen is found to have two absorption bands, viz. at wavelengths of 5 mm and 2.5 mm; water vapour shows absorption bands at various wavelengths in the mm range and at much shorter wavelengths. The absorption bands of interest to us are at $\lambda = 13.4$ mm and $\lambda = 1.64$ mm. This follows from investigations by J. H. van Vleck [4]), who studied the mechanism of this attenuation and calculated the numerical values as a function of wavelength. The curves in *fig. 6* give as a function of wavelength the attenuation suffered by radio waves in the atmosphere as a result of oxygen and water vapour. The values were calculated for a pressure of 76 cm Hg and a temperature of 20 °C. The relative humidity of the water vapour is taken as 100%. (The attenuation is of course less when the degree of humidity is lower.)

When the atmosphere contains water drops in the form of rain, mist and the like, there are two causes of attenuation:

a) energy is lost by *scattering* of the beam, and

b) energy is *absorbed* and converted into heat (dielectric losses).

In the case of water drops of very small diameter (fog, clouds) the attenuation is due mainly to absorption rather than scattering. The attenuation is then proportional to the quantity of water per m³. The attenuation due to these causes has been calculated by J. W. Ryde and D. Ryde [4]). *Fig. 7* shows the attenuation curves for different degrees of fog and rain as a function of wavelength.

Curve *3* in fig. 6, which gives the total attenuation without water drops, is seen to have a minimum at a wavelength of 8.2 mm. Since our radar equipment

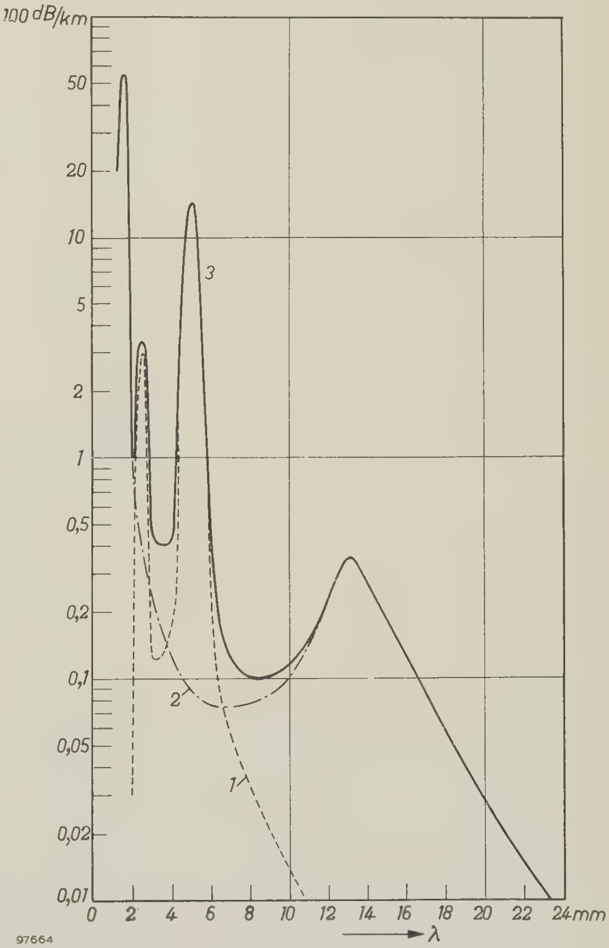

Fig. 6. Attenuation of radio waves by oxygen and water vapour in the atmosphere, as a function of wavelength. *1* = oxygen, *2* = water vapour, *3* = total attenuation (sum of *1* and *2*).

4) See e.g. D. E. Kerr, Propagation of short radio waves, Radiation Laboratory Series, No. 13, McGraw-Hill, New York 1951, Chapter 8.

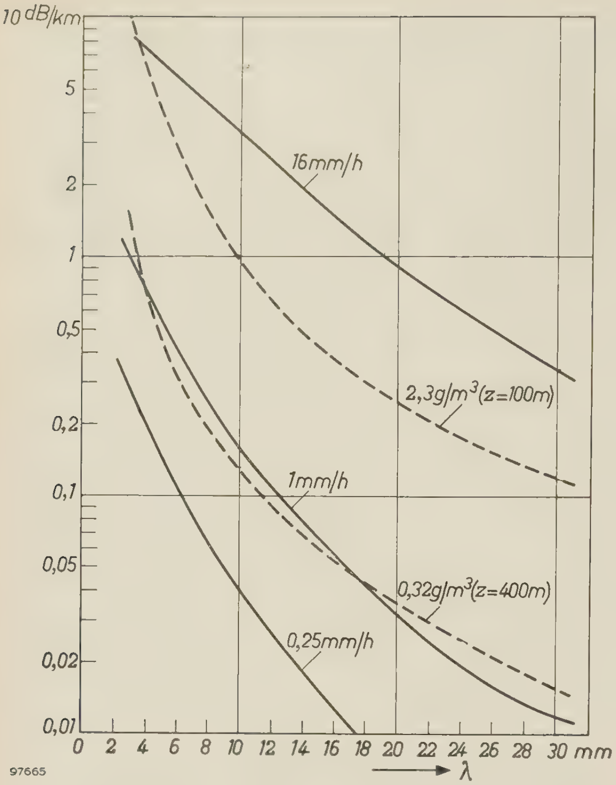

Fig. 7. Attenuation of radio waves caused by different degrees of rain and fog as a function of wavelength. The fully-drawn curves relate respectively to heavy rain, light rain and drizzle; the dashed curves relate to fog, grammes of water per m³ and the visibility z in metres being indicated.

is obviously to be used in rain and fog, the attenuation caused by water drops must also be taken into account, so that the minimum shifts to λ = 8.6 mm.

The fact that the minimum attenuation per kilometre is greater than in the centimetre range (e.g. 3 cm) is not a serious objection, the 8 mm radar installation being intended for short distances where the total attenuation is relatively small.

Description of the 8 GR 250 8 mm radar installation

The layout of the installation is illustrated in *fig. 8*. The transmitter, the receiver and the modulator plus drive stage are contained in a water-tight casing (*TMR*). On this casing are mounted the antennae and their driving mechanism. The antennae are rotated at a speed of 40 revs per minute. As already indicated in fig. 1, separate antennae are used in the 8 GR 250 for transmitting and receiving. In general radar practice, and even with 3 cm radar [5]) this is not usual, one antenna being used to which the transmitter and the receiver are alternately switched by a so-called duplexer (see *fig. 9*).

[5]) See Philips tech. Rev. **20**, 349-353, 1958/59 (No. 12).

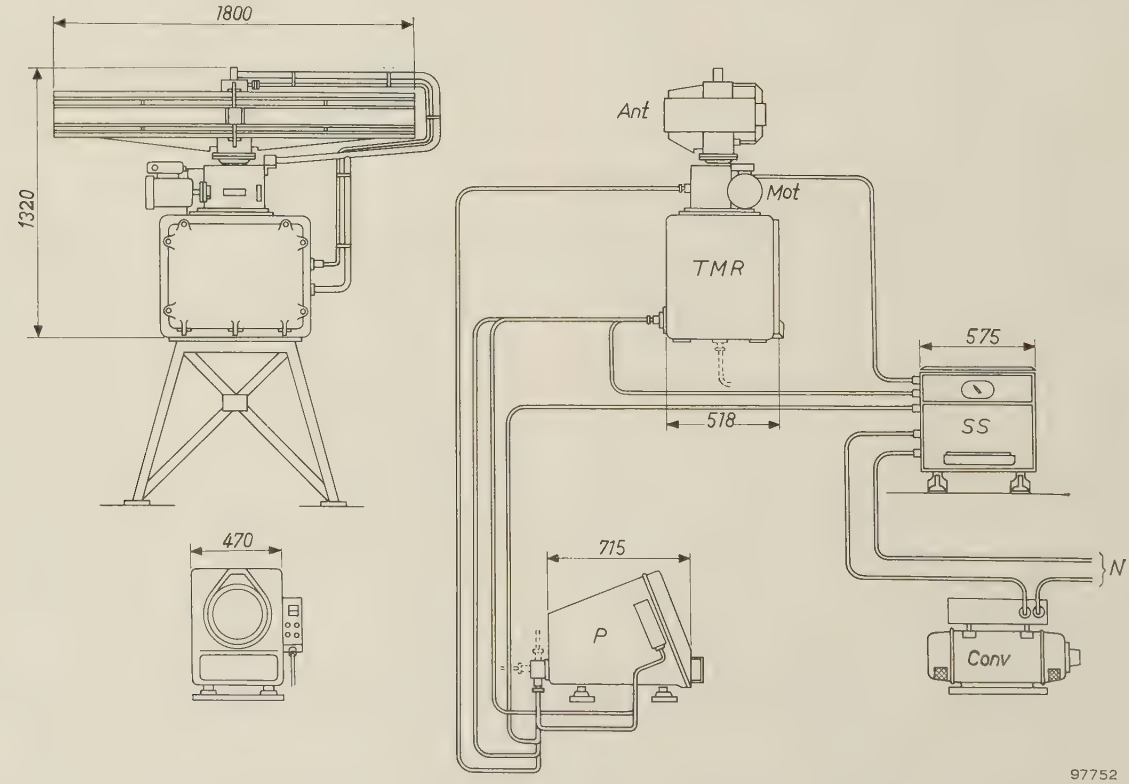

Fig. 8. Schematic layout of Philips 8 GR 250 8 mm radar installation. *TMR* water-tight case containing transmitter, modulator and receiver. Above the case are the two antennae *Ant* with drive motor *Mot*. *P* is the PPI unit. *SS* contains the supply circuits and the synchronizing pulse generator. *Conv* is a rotary converter supplying 120 V, 400 c/s. *N* mains connections. Front views of the *TMR* and *P* sections are shown on the left. Dimensions in millimetres.

A duplexer consists of two gas-filled tubes mounted in a special waveguide circuit. These open the transmitter channel and close the receiver channel while the pulse is being sent out, and reverse the process

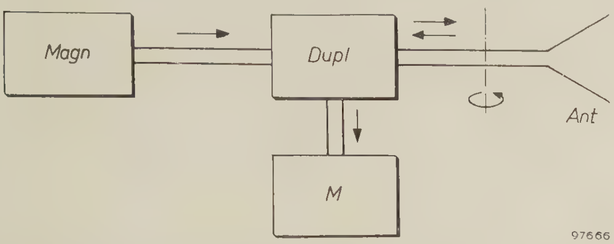

Fig. 9. Waveguide circuit with duplexer *Dupl*, as in a 3 cm radar installation using a single antenna for both transmitting and receiving. *Magn* = magnetron, *M* = mixer in receiver.

in the period between two transmitted pulses. The extinction time of these tubes is too long, however, to allow objects at very short distances to be observed, the reception channels still being closed upon the arrival of such early reflections. This is of course most undesirable for a short-range radar.

The antennae are two parabolic reflectors of the "cheese" type. Crosstalk between the receiving and transmitting antennae can be minimized by mounting the antennae at a specific distance apart. The result is that with relatively little trouble the minimum distance at which an object is seen can be made very small: one can even see on the PPI the feeder waveguide for the upper antenna (which inevitably comes into the beam because of the free rotation of the antennae).

The indicator unit (P) is shown bottom left in fig. 8. It consists of the cathode-ray tube with PPI screen, power pack, and the control panel on which, among other things, the radius of the swept area seen on the screen can be adjusted in steps. These radii are given in the table (next page); they differ for the two models mentioned at the beginning of this article, intended respectively for shipboard use or for airfield use.

On the right in fig. 8 can be seen the main power pack (SS), which also contains the synchronizing-pulse generator that determines the pulse repetition frequency of 5000 c/s. Below this is the rotary converter, which provides the supply voltage (120 V, 400 c/s).

The table below gives the principal data for the whole installation.

Turning again to the repetition frequency of 5000 c/s, the following may be noted. If we insert in formula (7) the appropriate values from the table, we find the minimum pulse repetition frequency F_{min} to be 800 c/s. This means that every object is scanned by about six pulses at a time, which is a reasonable number for obtaining a favourable signal-to-noise ratio. The maximum average power output of the magnetron is 7.5 W; from formula (6)

Fig. 10. *TRM* unit and antennae. The loop round the antennae is the feeder waveguide for the upper antenna.

Frequency band	34 512 - 35 208 Mc/s
Pulse length	0.02 µsec
Peak pulse power	25 kW
Pulse repetition frequency	5000 c/s
Intermediate frequency	90 Mc/s
IF bandwidth	50 Mc/s
Beam width of antenna: horizontal	0.3°
Beam width of antenna: vertical	17°
Speed of antenna rotation	40 r.p.m.
PPI	30 cm diameter
Radii of areas displayed on screen:	
A.S.M.I. type 8 GR 250/00	0.5 - 1 - 1.5 - 3 - 5 - 10 km (550 - 1100 - 1650 - 3300 - 5500 - 11000 yds approx.)
"Ship-shape" type 8 GR 250/01	0.3 - 0.5 - 1 - 2 - 3 - 5 nautical miles
Supply voltage and frequency	120 V, 400 c/s

it therefore follows that the maximum pulse repetition frequency F_{max} is 15 000 c/s. The pulse repetition frequency of 5000 c/s is thus sufficiently far below this value.

Fig. 10 shows a photograph of the watertight casing in which the transmitter, receiver and modulator are mounted. The whole unit is installed on the upper deck of a ship. The slots of the transmitting and receiving antennae above the casing are clearly visible in the photograph. The receiving antenna is the upper one.

approximately 15 kV; the magnetron draws a peak current of about 12 A. The modulator is designed to give the most favourable possible efficiency. The operation of the circuits involved will be discussed with reference to the diagram in *fig. 11*.

Our requirements for the modulator are the following.

1) We need rectangular pulses of the right shape and duration;

2) These must be of high voltage and considerable power;

3) The power must be stored in a reservoir which can be charged up again in the interval between two pulses.

These requirements are fulfilled here by two circuits: the driver stage, which generates the pulses, and the modulator proper, which converts these into pulses of high voltage and power.

As is well known, a good rectangular pulse can be achieved by taking a transmission line of specific length, charging it to a certain voltage and discharging it through a resistor. If the line is lossless and terminated by its characteristic impedance, this discharge will cause a constant current to flow through the resistor for a time that depends on the length of the line. This is the way in which the pulses are generated in the driver stage (see fig. 11). The

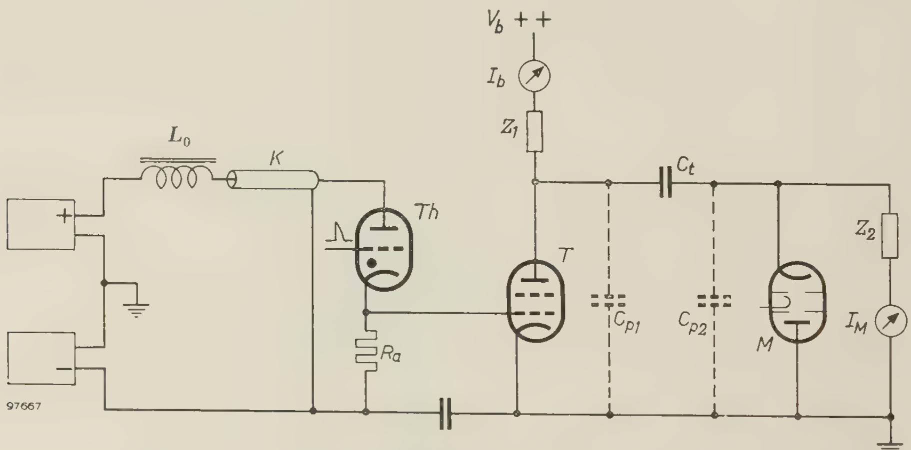

Fig. 11. Simplified schematic diagram of modulator and driver stage. M = magnetron, C_t = storage capacitor, T = tetrode, which functions as a short-circuiting switch, Th = thyratron, which connects the resistance R_a to the pulse-forming network (coaxial line) K at the appropriate moments, L_0 = charging choke, Z_2 = blocking impedance for magnetron filament supply, C_{p1} and C_{p2} = stray capacitances, responsible for much of the dissipation.

Some circuit details

Modulator

The Philips magnetron type 7093 [6]) used in the installation is modulated which voltage pulses of transmission line K is in this case a simple coaxial cable. This is possible because the pulse length is so short. If it were longer the cable would have to be very long indeed, and in that case use would preferably be made of an artificial line for which the velocity of propagation of electromagnetic waves is smaller.

The thyratron Th is the switch connecting the line K to the resistor R_a over which the voltage

[6]) This magnetron is described by J. Verweel and G. H. Plantinga, A range of pulsed magnetrons for centimetre and millimetre waves, Philips tech. Rev. 21, 1-9, 1959/60.

pulses appear. In the intervals between pulses, K is again charged up gradually via the choke L_0. At the appropriate moment the synchronizing-pulse generator (fig. 1), which determines the pulse repetition frequency, supplies a signal to the grid of thyratron Th. This is thereby made conducting and K discharges via R_a. This voltage pulse arrives on the control grid of the pulse tetrode T in the modulator circuit, causing this tube to pass a high current and the anode voltage to drop by about 15 kV until it bottoms to a value E_r. This negative voltage pulse is applied via capacitor C_t to the cathode of the magnetron M, which is thus triggered into oscillation. Since T must not conduct between the magnetron pulses, the supply circuit for the driver stage is so designed as to keep the control grid of T under constant negative bias. This is to be seen from fig. 11 (remembering that the thyratron is kept non-conducting at that moment). In connection with various protective devices is was found necessary to divide the power pack into two parts, indicated in the figure.

A particular feature of the modulator stage, which is basically of conventional design, is that the stray capacitances are kept as small as possible. The losses in the modulator occur in the tetrode T, and as a result of the repeated charging and discharging of the stray capacitances C_{p1} and C_{p2}. When a capacitor is charged from V_1 to V_2 an energy of $\frac{1}{2}C(V_2-V_1)^2$ is lost in the charging resistance, whilst an energy $\frac{1}{2}C(V_2{}^2-V_1{}^2)$ is stored in the capacitor, and this is also lost upon discharge. Since the pulse length is so short (0.02 μsec) the latter losses are important. We shall deal with this presently, but we shall first complete the description of the circuit in fig. 11.

The impedance Z_1 consists of a coil and a resistor in series; the object of this impedance is to protect the high-tension supply circuit (++) against short-circuiting during the pulse, and it also functions as the charging resistor for C_t. This capacitor is the reservoir earlier mentioned, which supplies the current to the magnetron during the pulse. This should have a minimum value such that at the end of the pulse the voltage over C_t has only dropped by a small fraction, is spite of the high current drawn by the magnetron. If, however, C_t is made larger than this minimum value, its capacitance with respect to earth also becomes greater. This earth capacitance partly contributes to the stray capacitance C_{p1} which also comprises the output capacitance of T and the wiring capacitance, and partly to the stray capacitance C_{p2}, which includes the input capacitance of the magnetron and the wiring and earth capacitance of Z_2. The impedanze Z_2 contains a coil and a charging resistor, which returns the magnetron side of C_t to earth potential after the pulse; the coil constitutes a blocking impedance in the filament supply lines to the magnetron, its purpose being to prevent the voltage pulse leaking away via these lines and via the earth capacitance of the filament current transformer. This circuit offers virtually no impedance to the filament current.

We shall now analyse the effect of the stray capacitances C_{p1} and C_{p2} more exactly and calculate the efficiency. We start from the quiescent state of the modulator. The high tension V_b is on the anode of T and on one side of C_t and C_{p1}. Both sides of the magnetron M and of C_{p2} and Z_2 are at earth potential. The tetrode T is cut off. As soon as tetrode T becomes conducting, C_{p1} discharges through T until the voltage has dropped to E_r, which is the bottomed voltage across T. In the same time interval the voltage across M increases to $-(V_b-E_r)$, which also applies to C_{p2}. The charge which C_{p2} thereby acquires is given up by C_t. During the magnetron pulse both C_t and C_{p2} lose part of their charge to the magnetron, but only a very small part, as already remarked. The voltage across M and C_{p2} therefore remains approximately equal to $-(V_b-E_r)$ during the pulse. After the magnetron pulse, C_t is charged and C_{p2} is discharged. It follows from the foregoing that the potential of C_{p1} is alternately V_b (between the pulses) and E_r (during each pulse). The corresponding values for C_{p2} are 0 and $-(V_b-E_r)$, if we disregard the insignificant role played by C_{p2} as storage capacitor during the magnetron pulse. We said earlier that this charging and discharging of capacitors costs a certain amount of energy. C_{p1} takes from the high-tension supply from pulse to pulse $C_{p1}V_b(V_b-E_r)$, which is a pure loss. In the same period C_{p2} receives $C_{p2}(V_b-E_r)^2$. Approximately, therefore, we can regard C_{p1} and C_{p2} as a single capacitance C_p. The efficiency of the modulator is now given by the ratio of the input energy to the magnetron for one pulse to the total energy dissipated during the pulse and between two pulses:

$$\eta \approx \frac{(V_b-E_r)I_{tm}\tau}{C_pV_b(V_b-E_r)+E_rI_{tm}\tau+(V_b-E_r)I_{tm}\tau}, \quad (13)$$

where I_{tm} is the peak current of the magnetron, τ is the pulse length and $E_rI_{tm}\tau$ is the loss in the modulator tube T. If we insert the following values: V_b = 16.5 kV, E_r = 1.5 kV, τ = 0.02 μsec, C_p = 23 pF, and I_{tm} = 12 A, we find η = 40%. The energy dissipated per pulse is proportioned as follows:

dissipation in the magnetron 3.6 mJ,
dissipation in the tetrode 0.36 mJ,
loss due to stray capacitances 5.7 mJ.

This clearly indicates the relatively important role played by the stray capacitances, and which is entirely a consequence of the short pulse length τ.

The efficiency can be checked during operation by noting the meter reading for the average magnetron current I_M and the average current I_b of the high tension supply.

Pulse correcting circuit

The echo pulse picked up by the antenna may suffer distortion as a result of reflection, the effect being that the pulse is elongated, i.e. it acquires a "tail". (The smaller the length of the wave train of the magnetron pulse with respect to the reflecting object, the greater the likelihood of tail formation.) This is obviously undesirable since it reduces the resolution of the radar system. For this reason the 8 GR 250 contains a pulse-correcting circuit, which can be put into operation when needed. The correction is obtained by adding to the elongated pulse a pulse of the same shape, but of opposite phase and of amplitude equal to the mean amplitude of the tail, delayed to an extent corresponding to the pulse length τ; see *fig. 12*. The result is a pulse whose tail is largely eliminated.

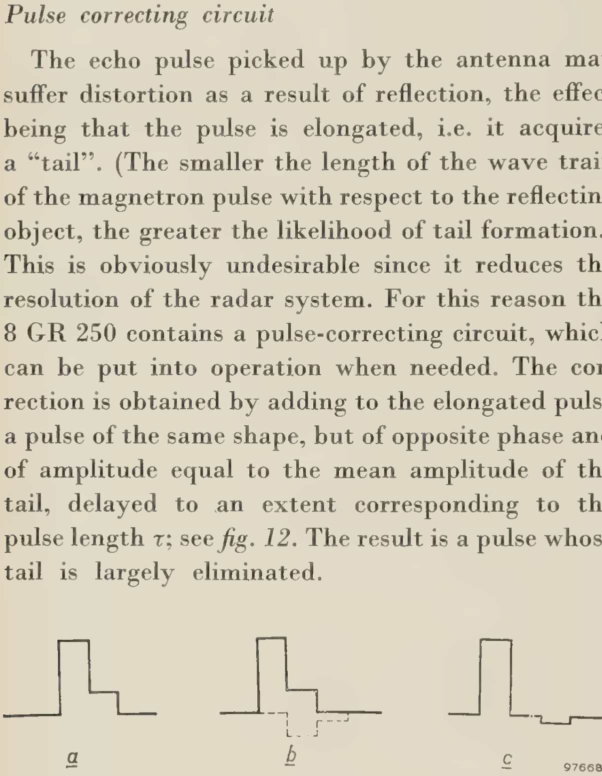

Fig. 12. *a*) Echo pulse with (idealized) tail. *b*) Delayed and inverted pulse added to (*a*). *c*) Corrected pulse.

This correction is effected by means of a four-terminal network as shown in *fig. 13*. (If necessary the procedure can be repeated with similar networks.) The network is placed in the coaxial video-

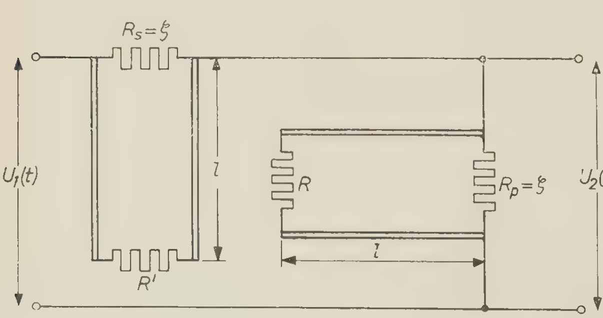

Fig. 13. Pulse-correcting network. Parallel with the series resistor R_s is a coaxial line of length l terminated by R'; parallel with R_p is likewise a coaxial line of length l, terminated by R.

Fig. 14. Radar display of a London dock area, taken with the 8 GR 250. The diameter of the display is adjusted for a coverage of half a nautical mile.

line, of characteristic impedance ζ, and is composed of a series and a parallel resistance of magnitude ζ. In parallel with each of these two resistors is another coaxial line of characteristic impedance ζ and electrical length $l = c\tau/2$, and terminated respectively by resistors $R' = \zeta^2/R$ and R. When a voltage $U_1(t)$ is applied to the input terminals, we can write for the output voltage $U_2(t)$:

$$U_2(t) = \tfrac{1}{2}\{U_1(t) + kU_1(t-\tau)\}\,, \quad . \quad . \quad (14)$$

where $k = (R - \zeta)/(R + \zeta)$. A suitable choice of k, that is of R, produces the phenomenon illustrated in fig. 12, for the formula indicates that we add to the original pulse a delayed pulse of the required polarity.

The formula given here can be simply derived with the aid of the theory of long transmission lines. In doing so we disregard the line losses. The input impedance is ζ. If the voltage on the input terminals be $U = U_1 e^{j\omega t}$, the voltage at the output terminals is:

$$U_2 = U_1\, e^{j\omega t}\, \frac{Z}{Z+\zeta},$$

where

$$Z = \zeta\, \frac{R + j\zeta \tan al}{\zeta + jR \tan al}$$

and $a = \omega/c$, $al = \omega l/c = \omega\tau/2$.

The form $Z/(Z + \zeta)$ can be written:

$$\frac{Z}{Z+\zeta} = \frac{1}{2}\left(1 + \frac{R-\zeta}{R+\zeta}\, e^{-j2al}\right).$$

Putting $(R - \zeta)/(R + \zeta) = k$, which can be either positive or negative, we find:

$$U_2 = \frac{1}{2}\left(U_1\, e^{j\omega t} + kU_1\, e^{j\omega(t-\tau)}\right).$$

Fig. 15. Radar display of apron at Schiphol airport, taken with the 8 GR 250. Screen set to $\frac{1}{2}$ km diameter ($\sim$ 550 yard).

Fig. 16. Radar display of Straits of Messina, taken with the 8 GR 250; screen coverage set to approximately 5 km diameter ($\sim$ 2.7 nautical miles).

Thus, if we apply a sinusoidal voltage to the input terminals we obtain at the output terminals half the sum of the input voltage U, increased by a fraction k of U which is delayed by a time τ (the pulse length) and is independent of the angular frequency ω. For an arbitrary voltage $U_1(t)$ each Fourier component of its spectrum will therefore suffer the same delay, and we obtain formula (14).

Performance of the 8 mm radar installation

The 8 GR 250 installation has been tried out in various circumstances and at many different locations. Some of the results are illustrated in photographs of the radar screen shown in this article.

Figs 2 and 3 show respectively the map and the radar display of Ymuiden Harbour. The opened lock-gates and other details of the docks are distinguishable on the radar screen [7]).

Fig. 14 shows the radar display of a part of the London docks. The area covered by the screen has a radius of about 900 metres. Here again, the high resolution of the apparatus is clearly brought out; one can see on the right, for example, the quays with ships alongside. At the centre even the shape of the s.s. Amstelstroom, on which the radar equipment was installed, can be roughly distinguished.

Fig. 15 shows a radar display of the apron at Schiphol airport (coverage radius 500 m). The shapes of some aircraft are clearly visible, and a ship can also be seen in the Ringvaart canal.

Finally, *fig. 16* was obtained on board a ship passing through the Straits of Messina. It can be seen that, in spite of the attenuation of 8 mm waves in the atmosphere, a good picture is also obtained of a larger area (radius of coverage about 5 km).

[7]) It is instructive to compare this with a 3 cm radar picture of Ymuiden as reproduced in Philips tech. Rev. **14**, 95, 1952/53.

Summary. When radar is used for very short ranges, for example in harbours, it is most desirable to be able to distinguish the shape as well as the distance of the surrounding objects. This means that the radar equipment must posses a high resolution. This can be achieved by using the shortest practicable wavelength, which makes it possible to obtain a pulse of extremely short duration and a beam of very small angular width. The radar equipment described, here Philips 8 GR 250, operates on a wavelength of 8.6 mm, which comes within a frequency region at which the atmospheric attenuation of millimetre radio waves has a minimum. Some general theoretical considerations are given with regard to the effect of wavelength on such properties as resolution, range and information capacity. An appropriate choice of such quantities as antenna dimensions (horizontal beam-width 0.3°), pulse length (0.02 µsec) etc., leads to a design in which the best compromise is achieved between the radial and tangential resolution of the radar system and the resolution of the PPI. The narrow beam entails the use of a high pulse repetition frequency. In the design of the modulator it was necessary to keep the stray capacitances as small as possible, since, owing to the short pulse length, these give rise to losses that are considerable compared with the power taken up by the magnetron. To ensure that the received pulse has a good shape under all conditions, a pulse-correcting network is incorporated in the video section of the receiver. Some photos of PPI displays illustrate the impressive results obtained with this equipment.

A METAL-CERAMIC DISC-SEAL TRIODE FOR FREQUENCIES UP TO 6000 Mc/s

by E. MENTZEL*) and H. STIETZEL*) 621.385.3.029.64

Since the completion of the EC 59 disc-seal triode [1]), work has proceeded on the development of a partly ceramic version of this microwave valve. The perfecting of the technique of bonding metals to ceramics has enabled very low loss resonant cavities to be produced. Moreover the use of a ceramic instead of glass makes it possible to increase the power output of grid-controlled valves, and also to raise the upper frequency limit — in so far as the latter is governed by valve geometry. On these lines a new disc-seal triode has now been made, provisionally designated as type OZ 92 and suitable for operation at frequencies up to 6000 Mc/s (*fig. 1*). The anode voltage is 500 V and the anode dissipation 125 W. The valve can be cooled either with water or with air. The power output at 5000 Mc/s is more than 10 W. The valve is not yet commercially available.

The requirements imposed on grid-controlled microwave valves are broadly: small inter-electrode spacings (to minimize transit-time effects); high transconductance; low valve capacitances (implying high specific loading of electrodes); and low coupling between grid-anode and grid-cathode circuits by optimum design of the grid (to achieve a high gain).

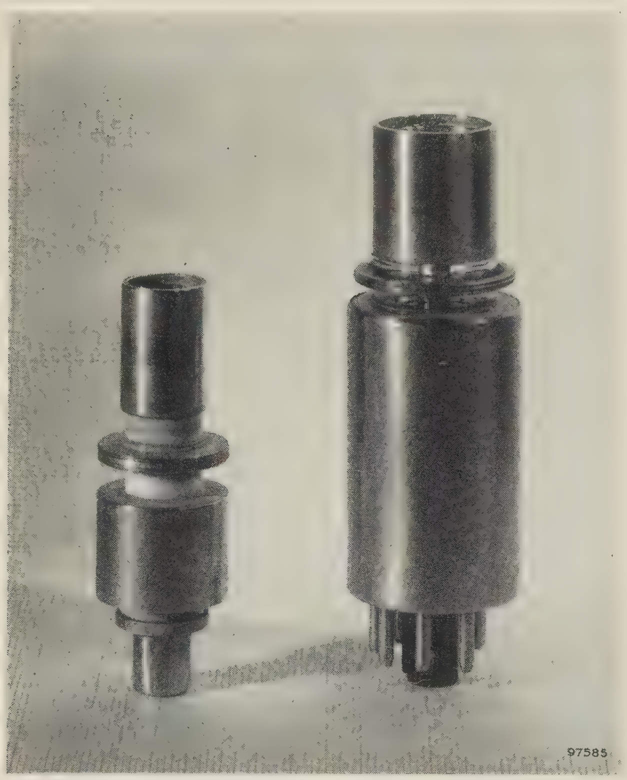

Fig. 1. Experimental disc-seal triode type OZ 92 with metal-ceramic wall (left) and disc-seal triode type EC 59 with metal-glass wall (right).

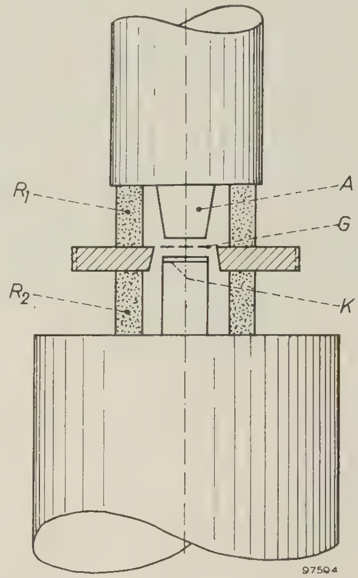

Fig. 2. Schematic cross-section of disc-seal triode OZ 92. *K* cathode, *G* grid, *A* anode, R_1 and R_2 ceramic rings.

Since disc-seal triodes are always mounted in resonant cavities, the shape of the valve wall influences the possibilities of tuning these cavities. The shape given to the valve envelope can therefore modify quite appreciably the upper limit of the useful frequency range.

As a material for valve walls sintered *aluminium oxide* ceramic offers considerable advantages, chiefly because the Al_2O_3-metal seals are capable of high thermal loading and Al_2O_3 has low dielectric losses even at high temperatures. The appropriate metal for the seal is an alloy of iron, nickel and cobalt. The solder used is silver or an alloy of silver and copper. The technology of metalceramic seals is now so far advanced that the kind of joint made — whether a flat or a collar joint — does not essentially affect the vacuum seal or its strength. The sealing technique therefore imposes little restriction on the design of the valve wall.

Fig. 2 shows the configuration adopted for the wall of the OZ 92. The design is based on the following considerations. In the first place it allows the valve to be mounted in conventional sections of waveguide, and in the second place, owing to the low expansion of the anode portion of the wall the electrode clearances retain the precision required even for very high frequencies. Some examples of

*) Development laboratory of the Valvo G.m.b.H. Radio Valve Factory, Hamburg.

[1]) V. V. Schwab and J. G. van Wijngaarden, The EC 59, a transmitting triode with 10 W output at 4000 Mc/s, Philips tech. Rev. **20**, 225-233, 1958/59 (No. 8).

this configuration are the disc-seal triodes EC 156 and EC 157 [2]), and the EC 59 [1]), already mentioned.

Features of the EC 59 taken over in the OZ 92 are the electrode dimensions and clearances; also the new valve is run under the same D.C. conditions. The frequency limit is thus fixed, in so far as it is determined by electrode clearances and diameters. The frequency limit being fixed, the outside dimensions of the valve follow mainly from two requirements:

1) The resonant cavity should oscillate in the fundamental mode (E_{010} resonance of the capacitatively loaded cylindrical cavity).
2) The surface area of the valve wall where high-frequency current flows must be made as small as possible in relation to the total surface area of the resonant cavity.

The second requirement is a consequence of the fact that, in the walls of a capacitatively loaded E_{010} resonant cavity, only weak currents flow near the axis, so that even if the conductivity of the surface there is poor, high losses are not incurred in this part of the wall; contact resistance losses are also negligible near the axis. Ohmic losses in parts of the cavity walls farther from the axis can be minimized by improving the surface (silver-plating, polishing). The Q of a resonant cavity depends on its form and on the electrical losses. The E_{010} mode being the fundamental mode, the Q of such a resonant system is optimum when the height of the cavity is approximately half the diameter. On the basis of these data we can calculate the geometrical dimensions. At the given values of grid-anode separation (h, see *fig. 3*) and anode diameter (d) we find for 5000 Mc/s the diameter (D) and the height (H) of the cavity as given in the caption to fig. 3.

The ceramic rings for the valve wall have an outside diameter of 11.6 mm, a thickness of 1.6 mm and a height of 6 mm. These dimensions are the

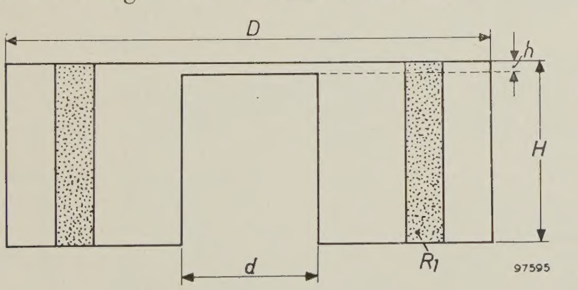

Fig. 3. Schematic cross-section of anode resonant cavity of disc-seal triode with ceramic ring R_1. The Q of the resonant cavity is optimum when $H \approx \frac{1}{2}D$ The following are the dimensions of the 5000 Mc/s cavity of the OZ 92 : H = 6 mm, D = 16 mm, h = 0.30 mm, d = 4.5 mm.

[2]) Valves EC 156 and EC 157 differ from the older types EC 56 and EC 57 in their cathode, which has a longer life. The EC 57 is described in Philips tech. Rev. **18**, 317, 1956/57.

result of a compromise between the need to make the valve as small as practicable and the fact that the ceramic material, owing to its high dielectric constant (ε_r = 10), would constitute a considerable capacitative load on the valve if the dimensions were unduly small, thereby lowering the Q of the anode resonant cavity. For the dimensions given the limit frequency of the finished valve wall at the grid-anode side is 6500 Mc/s.

To minimize the surface area of the resonant cavity, protruding edges, projecting metal parts and similar irregularities are avoided as far as possible. The high ohmic losses of the Fe-Ni-Co alloy used are eliminated by gold-plating the surface (to a thickness of 3 to 5 μ). As a result of these measures the Q of an unloaded grid-anode cavity of the form shown in fig. 3, with valve walls prepared as above was found to be about 500 at 5000 Mc/s. This is roughly twice the figure obtained with glass-walled valves, and for the conventional applications it means an increase in circuit efficiency of approximately 10%.

The OZ 92 triode consists of four sub-assemblies (*fig. 4a, b, c, d*) with altogether 15 components (corresponding glass-walled valves have some 30 components). All assembly operations are straightforward and can be carried out with the necessary precision by semi-skilled personnel equipped with simple tools and jigs. This simplification of construction and assembly is largely attributable to the good resistance to deformation of the ceramic material in the temperature range below 1000 °C.

The anode assembly (fig. 4*a*) consists of the anode, a ceramic ring and the upper part of the grid disc (the lower part of which belongs to the external cathode assembly). Making the grid disc in two parts simplifies the adjustment of the electrode clearances, the cleaning of internal surfaces of the valve and the finishing of the grid seating. The anode, too, is in two parts, for the practical reason that the Fe-Ni-Co alloy used cannot withstand the high thermal load (1.9 kW/cm^2) to which the anode proper is subjected during outgassing on the pump. The anode proper is therefore made of molybdenum. For locating the ceramic ring, the anode and the grid disc are recessed (0.8 mm) which strengthens the structure without significantly increasing the ohmic losses.

Fig. 4*b* shows the external cathode assembly. It comprises the lower part of the grid disc, a second ceramic ring, the cathode sleeve, a third ceramic ring and the outer conductor of the concentric heater-supply system. The metal-ceramic joints in this assembly are similar to that in the anode system. The cathode bush carrying the cathode proper

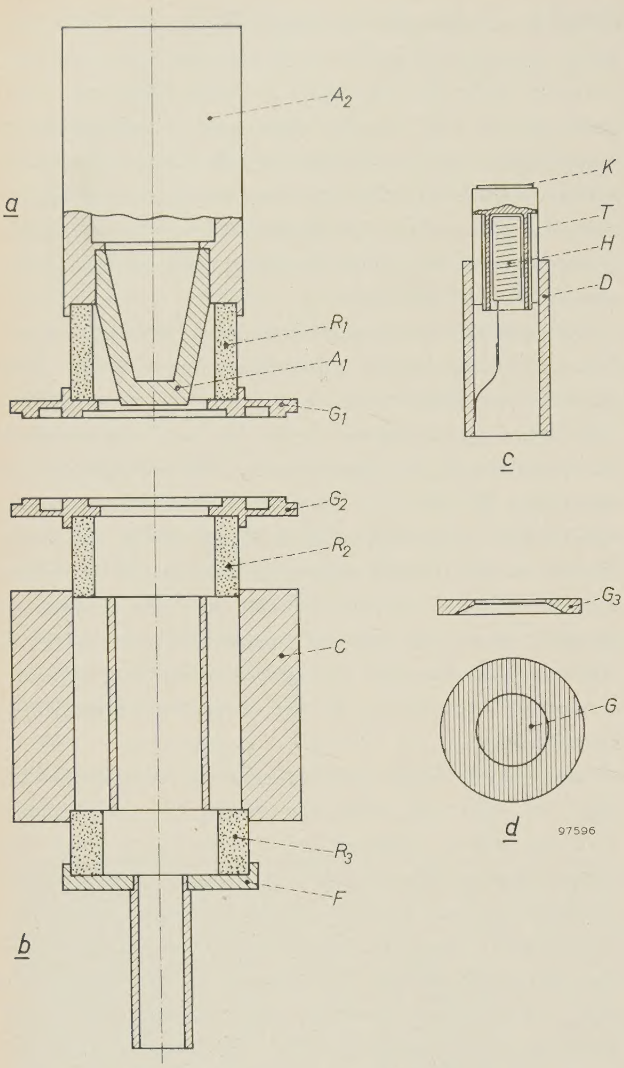

Fig. 4. The four sub-assemblies making up the OZ 92.
a) Anode assembly with anode $A_1 + A_2$, ceramic ring R_1 and upper part G_1 of grid disc. Part A_1 of the anode is of molybdenum, part A_2 is an alloy of iron, nickel and cobalt.
b) External cathode assembly, with lower part of grid disc, ceramic rings R_2 and R_3, cathode sleeve C and heater connection F.
c) Internal cathode assembly, with dispenser cathode K, heater H, tantalum cylinder T and cathode bush D.
d) Grid assembly, with grid G of tungsten wire wound on the ring G_3.

fits into the cathode sleeve (fig. 4*c*). The cathode bush contains the dispenser cathode, the latter being enclosed in a tantalum cylinder which prevents the penetration of evaporated barium into the grid-cathode space and also acts as getter.

The grid assembly can be seen in fig. 4*d*, and consists of the grid-frame wound with fine tungsten wire. The frame is circular and automatically centres the assemblies *a* and *b*. The thickness of the frame determines the spacing between grid and cathode. In the final assembly stage, sub-assemblies *a* and *b* are joined together by high-speed silver-soldering of the two grid disc G_1 and G_2 along their peripheries (speed being necessary to prevent too much slackening in the tension of the tungsten wires).

The D.C. data and other particulars of the OZ 92 are listed in *Table I*. *Fig. 5* shows the I_a-V_g characteristic of an average valve.

Table I. Data of the OZ 92.

Heater voltage V_f	6.3 V	Transconductance S	approx. 17 mA/V
D.C. andode voltage V_a	500 V	Amplification factor μ	approx. 28
D.C. anode current I_a	250 mA	Valve capacitances:	
D.C. grid bias V_g	—5 V	C_{gk} = 3.3	pF
Anode dissipation P_a	125 W	C_{ag} = 1.9	pF
		C_{ak} = 0.048	pF

Because of the high thermal conductivity of Al_2O_3 and the absence of electrolysis, even at high temperatures, the OZ 92 can be subjected to a very heavy thermal load. The temperature of the metal-ceramic joints, however, must not exceed 250 °C (in the case of the EC 59 the temperature of the glass seal must not rise more than 120 °C above ambient.) This requirement can be met by water-cooling and also by air-cooling. *Fig. 6* shows the temperature of a seal above the ambient as a function of anode

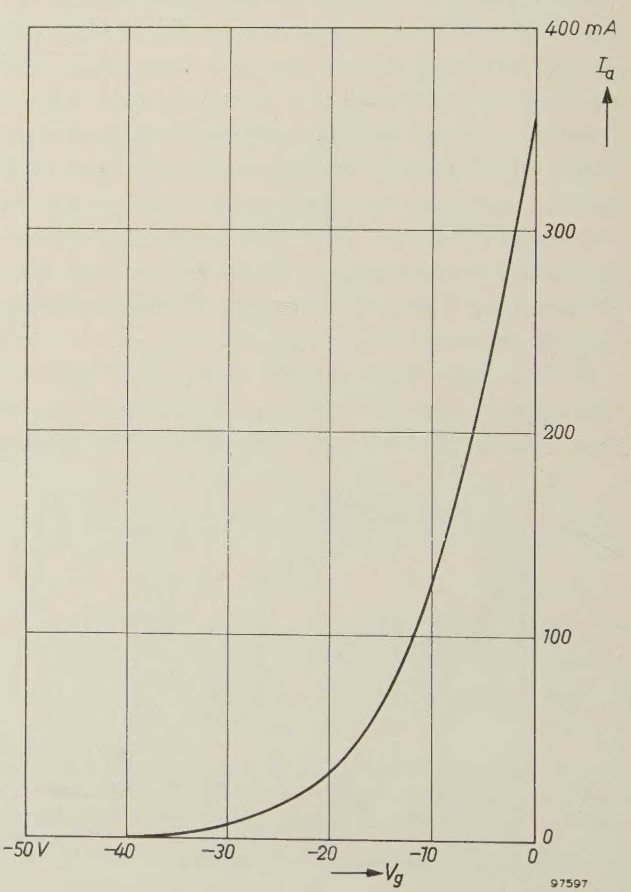

Fig. 5. D.C. characteristic of the OZ 92: anode current I_a as a function of grid voltage V_g, at 500 V anode voltage and 6.3 V heater voltage.

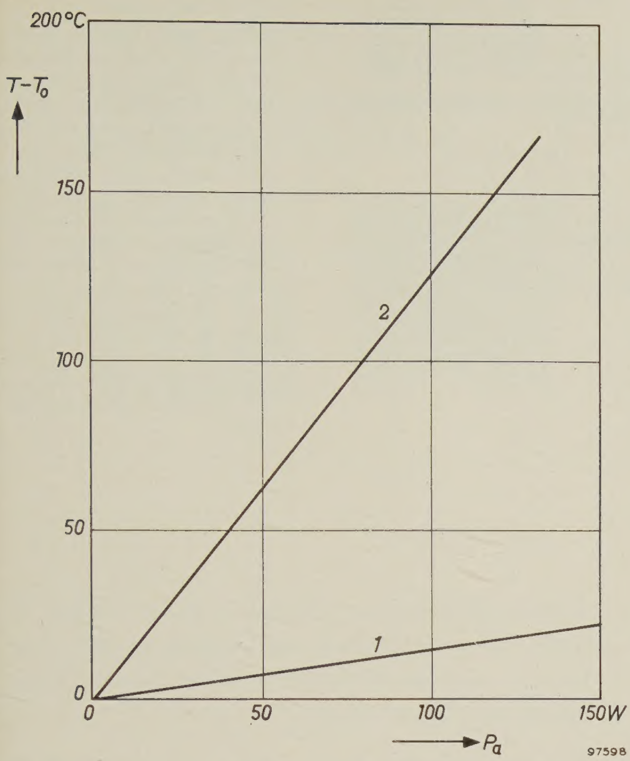

Fig. 6. Temperature difference $T—T_0$ between anode metal-ceramic seal and ambient, as a function of anode dissipation P_a. Curve *1*: water cooling (0.5 l/min); curve *2*: air cooling (40 l/min).

dissipation using experimental cooling systems. The temperature was measured in the immediate proximity of the metal-ceramic seal on the anode.

Another favourable property of the valve is its insensitivity to rapid fluctuations of temperature. This is due to the fact that the expansion coefficients of Al_2O_3 and the Fe-Ni-Co alloy used are virtually identical.

The valve can operate either in amplifier or oscillator circuits up to 6000 Mc/s. *Fig. 7* shows a test set-up with the OZ 92 as an oscillator. The oscillator is of the re-entrant type (*fig. 8*), the frequency being changed by inserting another resonant cavity in the output circuit. Some results obtained with this oscillator are given in *Table II*.

Table II. Experimental results obtained with an OZ 92 in an oscillator circuit, with an anode voltage of 500 V.

Frequency f	(Mc/s)	4740	4980	4990	5470	5530
Power output P_o . . .	(W)	7.1	12.4	13.2	4.8	6.9
Anode current I_a . .	(mA)	235	255	320	196	290
Grid bias V_g	(V)	−25	−17.5	−28	−31	−5
Grid current I_g	(mA)	30	20	33	19	23

The power output of the oscillator falls off at both sides of the frequency band around 5000 Mc/s. Towards higher frequencies the fall-off is presumably due to valve properties, and towards lower frequencies it is attributable to the properties of the oscillator.

The measured outputs in the oscillator circuit — viz. 13 W at 5000 Mc/s and 7 W at 5500 Mc/s, roughly corresponding to efficiencies of 9% and 5%, respectively — prove that the OZ 92 still operates quite satisfactorily at these frequencies.

However, the valve is not primarily intended for use as an oscillator but, like the EC 59, as a *power*

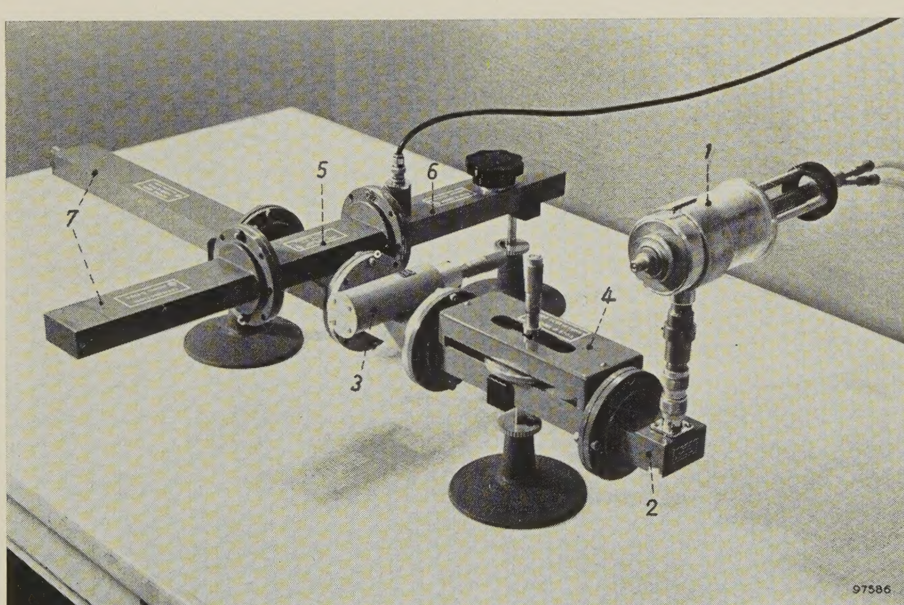

Fig. 7. Test set-up with the OZ 92 operating as an oscillator. The photograph shows the oscillator *1* (cf. fig. 8) and associated waveguide components for measuring purposes: transition section *2*, frequency meter *3*, matching section *4*, cross coupling *5*, thermistor termination *6* and matching impedance *7* for the G band (3950-5850 Mc/s).

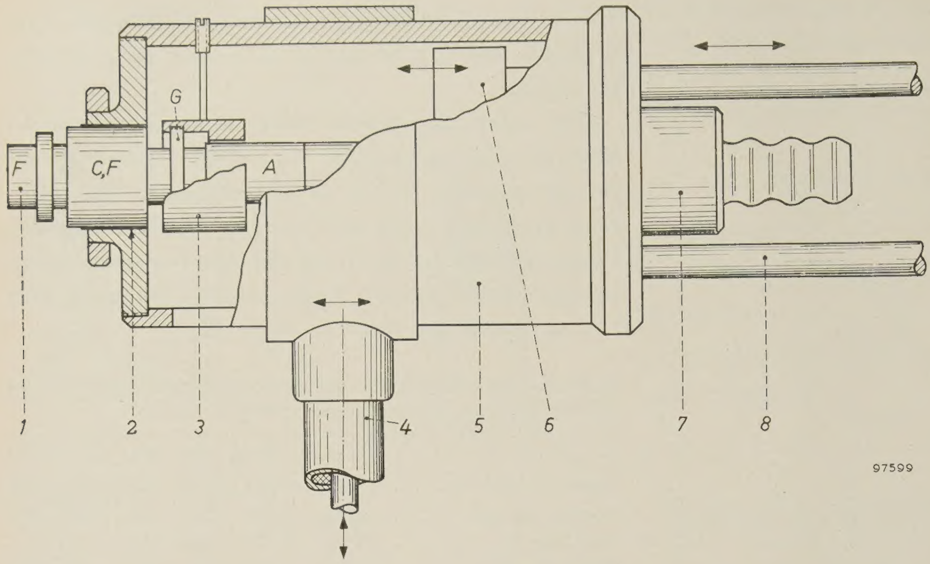

Fig. 8. Oscillator with re-entrant type of cavity, using the OZ 92. *1* disc-seal triode OZ 92. *2* decoupling capacitor. *3* cylindrical bush forming anode resonant cavity. *4* output probe movable axially and radially. *5* outer resonant cavity, also forming the grid connection. This cavity is coupled to the anode resonant cavity by the annular gap between *A* and *3*. *6* tuning plunger for outer cavity (not in contact with *5*). *7* coolant duct, also forming the anode connection. *8* guide rods of tuning plunger.

amplifier. It might, for example, be used with advantage in the G band (3950 - 5950 Mc/s). It behaves electrically rather like the EC 59, but because of its different shape it is not directly interchangeable with it. A simple amplifier designed for inclusion in a waveguide system can be seen in *fig. 9*.

Summarizing it may be said that the advantages of the OZ 92 are due to its walls of aluminium oxide ceramic, the properties of which are superior to those of glass. The advantages of the OZ 92 are:

1) Higher permissible thermal loading, owing to better heat conduction and rigidity of the ceramic. No electrolysis in the ceramic, even at high operating temperatures.

2) The low dielectric losses of the ceramic result in resonant cavities of higher Q.

3) The resistance of the ceramic to deformation at high temperatures makes possible a simple construction with only 15 components.

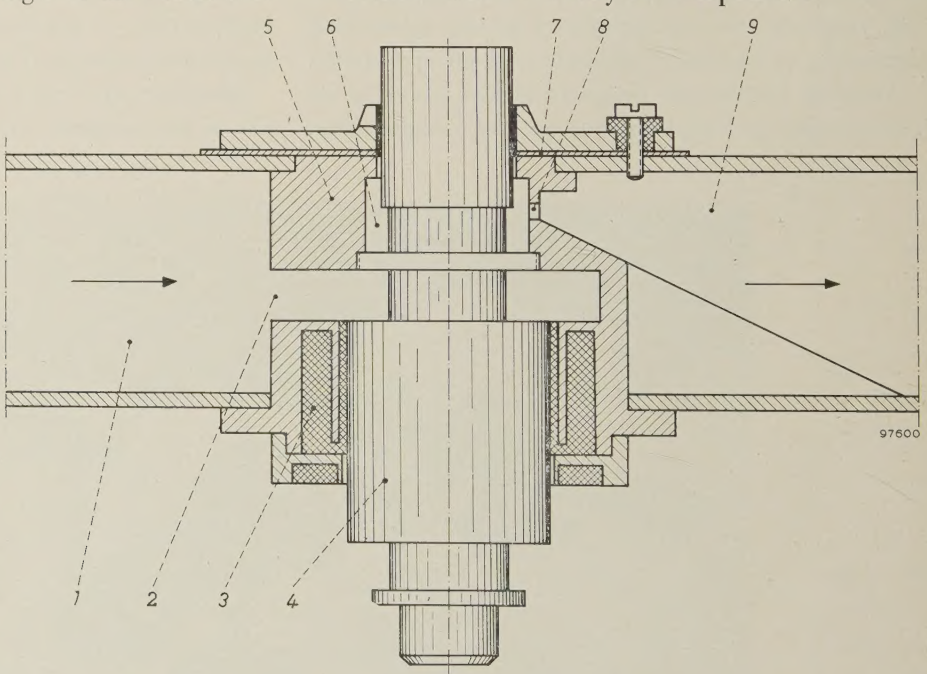

Fig. 9. Illustrating the principle of an amplifier based on the OZ 92 incorporated in a wave-guide system.
1 amplifier input. *2* input circuit. *3* "choke" insulation. *4* disc-seal triode OZ 92. *5* amplifier block. *6* output resonant cavity. *7* decoupling capacitor. *8* coupling slot. *9* output waveguide.

Summary. Description of an experimental disc-seal triode developed in the Valvo laboratory in Hamburg and provisionally designated as type OZ 92. Its electrode system is the same as in the EC 59, but its wall is of ceramic (Al_2O_3) and metal (an Fe-Ni-Co alloy). The advantages of ceramic over glass are: 1) higher thermal loading permissible owing to better heat conduction, and no electrolysis, even at high temperatures; 2) lower dielectric losses; 3) greater resistance to deformation at high temperatures. These advantages have led to a valve of very simple design, capable of delivering more than 10 W at 5000 Mc/s. The anode dissipation is 125 W, for which either water or air cooling is adequate. Anode voltage 500 V. The maximum permissible temperature of the metal-ceramic seals is 250 °C.